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ELECTRIC DISTRIBUTION FUNDAMENTALS

BY

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FIRST EDITION
FOURTH IMPRESSION

McGRAW-HILL BOOK COMPANY, INC
NEW YORK AND LONDON
1940

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THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

Distribution facilities of the electric light and power supply industry have had a steady growth, with an especially great physical expansion during the past 15 or 20 years. This expansion, accompanied by the necessary organization and specialization of work and effort, has made it difficult for many engaged in the industry to follow the remarkable development of methods and equipment. It is natural that the majority of books, magazine articles, and engineering papers concerning electric distribution should be directed primarily to the attention of engineers and supervisors responsible for planning and operating the systems.

This book is intended primarily for the men on the job, both in electric distribution divisions of the utilities and in the industrial wiring and commercial contracting branches of the broad field of distribution to the outlet. On these men—foremen, linemen, electricians, troublemen, repairmen, inspectors—rests, in a large measure, responsibility for continuation and extension of the high standards of reliability and quality of electric service.

It is hoped, too, that others who have frequent contacts with electric distribution practices, through their work in sales, purchasing, accounting, or other allied activities, will find this explanation of principles helpful.

The purpose here is to approach the subject from the fundamental point of view and to develop the perspective, historical, and economic background of electric distribution as a part of the general system of electric supply.

Graphical methods of solution are used for typical problems of line design. Essential theory is explained largely by means of comparison and analogy. Reference to formulas based on trigonometry, calculus, etc., is avoided. However, there are included many problems that require a working knowledge of voltage drop, wire size calculation, transformer connections, inductive reactance, power factor, etc. Emphasis is given to the everyday problems and their relation to the standards and practices that have followed many operating and economic comparisons in past development.

Many of the essentials of distribution engineering and design must be given only slight attention in this treatment. It is possible, though, that the fundamental explanations will help students, junior engineers, draftsmen, estimators, and others, to relate their mathematical and engineering studies with the specialized field of distribution. The graphical solution methods have the advantage of clarifying the factors involved, which is the first essential in any of the more exact mathematical methods of solution.

The foundations for this material are notes and review sheets prepared for discussion in educational and group meetings in the Cincinnati Gas and Electric Company, during the past ten years. A number of reports and articles prepared in the company have also been used for reference material. The author is indebted to the late Mr. F. R. Healey and to Mr. P. B. Stewart for suggestions and encouragement in this work. Thanks are also due to several associates for reviewing the manuscript and to the General Electric Company for a number of material suggestions and several illustrations included in the text.

"Electrical Distribution Engineering" by Howard P. Seelye has been a source of factual information in preparing for the discussions. Reports and papers of the Edison Electric Institute and the American Institute of Electrical Engineers have been consulted in preparing for the discussions of developments and practices. "The Overhead Systems Reference Book" (of former N.E.L.A.) has been referred to for many of the definitions and tabulated data.

FRANK SANFORD.

CINCINNATI, OHIO,
January, 1940.

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ELECTRIC DISTRIBUTION FUNDAMENTALS

CHAPTER I

PERSPECTIVE OF THE ELECTRIC SYSTEM

Electric distribution, in its broadest meaning, is the provision of paths from electrical generators to equipment that utilizes electricity. It includes high-voltage transmission lines, substations, feeder circuits, transformers, service lines, protective and switching equipment, and wiring to the lamps, motors, and heating appliances. For purposes of specialization, it is commonly referred to as that part of the utility supply system between the major substations and the customers' meters.

Fundamentals in the layout and operation of the distribution wiring on the load side of the meter are essentially the same, and actually there are probably more miles of wire there than on the supply side of the meter. Fundamentally, there is no break in the flow of electrical energy from the generator to the appliances; but, to get a complete picture and also to deal with the more complex details of design and operation, it is most convenient to consider the system in several divisions.

From the standpoint of system layout and expansion, electric distribution is the first division. Electric system facilities are constructed and expanded to serve the customers' loads. Where the customers build their homes, stores, and factories and the load they connect to the service lines, determine not only the location and size of distribution lines and substations, but also the transmission and generating plant layout and capacity.

The function of electric distribution is to deliver to those who can use electric current and who need it to operate lights, motors, and appliances the energy that can be most efficiently generated in a central station. Distribution is the movement of goods from where they can be made at the lowest cost to where they can be used to advantage. All distribution systems add to the manufactured products an economic value o lace utility.”

Mechanical power has been the foundation of our i l age, and electric power transmission and distrib h n the foundation for its widespread use in ou ng. Power, with water wheels and later with t steam e of James Watt (about 1770) as the prime mover, had a distinct limitation until means were discovered to carry it over distances measured in miles. It was possible to transmit power a few feet, or at most a few hundred feet, with gears, shafts, and belts. Our modern industrial development has followed the removal of this limitation.

Electricity is a manufactured product in common with other products of our manufacturing and economic system. Our manufacturing, transportation, and distribution systems have been built up along the lines of the most economical and efficient practice. Our electric system, as we know it today, is the result of many years of development, and each change and ition have been the result of economic or cost comparisons wi possible methods.

Among the servants of mankind, electricity is one of m st outstanding—as well as one of the newest. Water, coal, steam, gas, minerals, and many other utility resources were advanced and used before the first developments in electrical generation and distribution were known. Electricity has, to a considerable extent, displaced many of the older forms of energy in general use. The widespread use of electrical energy and its importance to practically every individual make it advisable for those charged with promoting its further extension and use to see perspective the electric supply system.

This need of a broad view of electric supply is particular important for those engaged in the distribution division. Our contacts with our customers, our plans for line e the location of new distributing centers, and, in any of our daily tasks are more successfully carried o if we keep in mind where the results of our efforts fit int al picture. An inspector for a line extension may be sim y trying to locate spots for poles to be set, or he may be layi out an electric supply line to serve lights and appliances in a section of homes. Needless to say, the latter attitude is more likely to lead to enjoyment in his work and to his advancement.

Next in importance is an understanding of the uses of electric service. This does not require a detailed knowledge of load equipment characteristics, but we should know enough about them to appreciate the special problems associated with different apparatus. One need not be a radio engineer to have enough general knowledge of rectifier characteristics to be at ease in discussing with the customer's engineer service requirements, voltage, location of transformer stations, etc., for a new broadcast transmitter; nor need one be a heat-treating expert to appreciate the special requirements of electric furnaces and their service from the distribution lines.

Electricity, although it is invisible, is a manufactured product. It is a force or energy made from the energy stored in coal or falling water. Because our wires and transformers are rather lifeless looking, it may be difficult to realize that they are serving the same function that railroads and roads serve for other manufactured goods. Our lines are like the rails, but what they carry has not the appeal to the public understanding that the speeding train has. And although their purpose is like that of the roads, here again our product lacks the color and life of the automobiles that use the roads.

But we know that they are very much alive and that the electrical energy, although we cannot see it, is ready to do almost any of our work for us. If we can visualize the generation, transmission, and distribution of electrical energy as being equivalent to the manufacturer's transportation and delivery of the goods that we can see, it will help us to understand the system, as well as to make it more interesting to others.

DEVELOPMENT OF THE ELECTRIC SYSTEM

The first regular distribution of electricity on a commercial basis in this country was started on Sept. 4, 1882. Thomas A. Edison had developed a complete line of equipment, from generators to lamps and including the necessary fixtures, meters, switches, etc., to install a direct current system with underground conductors. The plant was located on Pearl Street in New York City and supplied an area of about one-half mile radius around the station. Previous to this, Edison and his associates had built a small experimental plant with electric lamps and lines at his laboratory at Menlo Park, N. J. A station using the Edison system was started in England at about the same time.

While other inventors had worked on parts of an electrical system, Edison had developed a complete line and put it into operation. This followed Edison's perfection of the first successful incandescent lamp in October, 1879. Electricity generators and arc lamps were in use for some years before this, and motors had been used since 1876.

All our generator, motor, and transformer developments have been based on the experiments of a few physicists, notably Michael Faraday, a little over one hundred years ago. Faraday discovered the action that led to the theory of magnetism, but it was nearly fifty years later that Edison brought this discovery into wide commercial importance. Within a few years after Edison's pioneer station was started, many other stations were built, using the system of the Pearl Street station and licensed under the Edison patents.

The principal differences between the electrical systems of today and these original systems are based on the use of alternating current instead of direct current. With the direct current system, the generator and distribution lines had to be operated at the voltage that was used by the lamps of the customers. Voltage drop limited the practical radius of the territory served to less than a mile.

The alternating current system is built around and based on the use of transformers. Many engineers realized the limitations that were placed on electrical distribution by the direct current system. The next step in the development required the invention of an entirely new device. In 1885, George Westinghouse purchased the patents of a crude transformer built in Europe, and he and his associates began the development of the present type of transformer. Since that period, improvements in design have been made, but the principle and general idea of the transformer have remained the same.

Transformers make it possible to use higher voltage for the transmission and distribution of electrical energy by permitting the stepping up and the stepping down of the voltage at the generating and at the receiving end of the line, respectively.

Since transformers can be used only with the alternating current system, development of the transformers naturally led to the gradual increase of alternating current systems and final dropping of the direct current systems. Alternating current circuits and the use of transformers have greatly extended the possibilities of central station distribution.

The first commercial alternating current systems were put into operation in 1886, in Great Barrington, Mass., Mar. 16, and in Buffalo, N. Y., Nov. 30. Although direct current systems are still in operation in some of the older business areas of a number of our larger cities, the alternating current system has completely superseded the direct current system for general use. Where the direct current systems are still in operation, they are supplied by converters from the alternating current distribution systems. There are a number of utilization applications that work better with direct current; in such cases, converters are used from the alternating current supply.

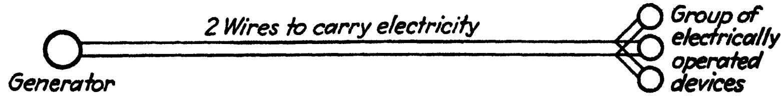

2 Wires to carry electricity
Generator
Group of electrically operated devices

FIG. 1.—Fundamentals of the electric supply system.

These early electric supply systems had two divisions—generation and distribution (Fig. 1). The area served by each of the central stations was very limited, there often being as many as 5 or 10 power plants in one city within a distance of a few blocks of each other, serving only the more densely populated section and principally for business, commercial, and small industrial uses. The next step was to install a transformer at the sending end and with the higher voltage extend the distribution lines out along one of the main thoroughfares to reach residential sections. A second transformer was then installed to step the voltage down to that of the house wiring, a number of customers being served from this transformer (Fig. 2).

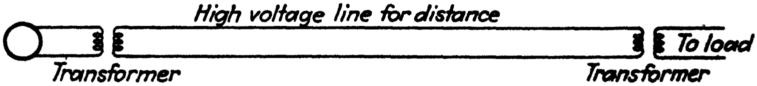


FIG. 2.—Transformers were added to increase possible area of distribution by use of higher voltages.

By about 1900, the general public was convinced that electrical supply was a business that was here to stay, and the gas companies were convinced that they had real competition in the form of electric light. Engineering development had made possible the extension and consolidation of many of the smaller central stations and distribution circuits. These factors, coupled with the understanding that had been obtained of the economic factors, such as investment, rates, and probable revenue, had led to many consolidations of the companies as well as of the physical systems. It is approximately that period which marks the beginning of the electrical supply system as we know it today.

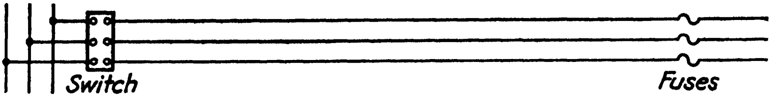


FIG. 3.—Oil switches, relays, and fuses are used for protection so that trouble is confined to the branch, feeder, or section where a fault occurs.

We have noted that transformers for changing the voltage of the supply system were added to achieve distance in distribution. As distances increased, it was also essential to develop equipment to prevent trouble on one circuit from causing outages and interruption of service to other circuits (Fig. 3). Protective devices were developed which have led to the quick acting switches and relays that we have today. Three-phase circuits, as shown in Fig. 4, were another development for economy in the supply lines and equipment. To maintain constant voltage or pressure of the supply on long lines, voltage regulators have been added (Fig. 5). To minimize and gradually to eliminate the troubles caused by lightning, arresters have been added to the equipment to carry the lightning discharge current to ground.

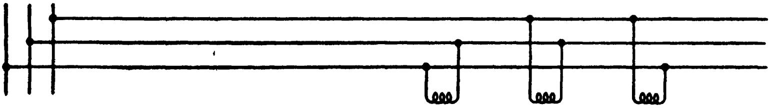


FIG. 4.—Three-phase is used for economy in supply lines.

FIG. 5.—Voltage regulators added to maintain even voltage as load on the line changes.

Gradually, the original distribution lines about the business areas of the cities were extended farther and farther out, and branches were built on side streets. In time, these lines became so long and so loaded that it was necessary to take the next step, which was to use a still higher voltage to carry the bulk load out to the suburbs. At these points, substations were installed, with transformers to step the voltage down to that of the distribution lines, which in turn supplied the transformers in the neighborhoods. This expansion required the development of equipment to be used in the new substations.

Thus the system grew because of the distance that the energy was being sent. The first simple idea of a pair of wires, carrying the energy at the voltage at which it could be used, was developed further and further as more load was added and as distance was achieved.

Great strides have also been made in the generating end of the electric system. Reciprocating steam engines gave way to the high-speed turbines. Steam pressures and temperatures were greatly increased. The capacity of the generating equipment was increased, and the generating voltages were raised. These innovations led to two fundamental changes in the general system design and arrangement. (1) It was evident that it is necessary to have the plant located where there is an abundant supply of condensing water for the most efficient operation of the boilers and turbines. (2) The larger units and the more efficient use of the power plant facilities led to the abandonment of many of the small plants in favor of one or two favorably located plants for each of the large supply areas.

Figures 6 and 7 show the alternative arrangements of electric supply in a metropolitan area, based on the generating plant economy. First, we have several generating plants, each serving its own load area by means of distribution feeders. With the second arrangement, we have the several generating plants replaced by substations, each supplying the distribution feeders for its load area. These substations are then supplied by transmission lines from one large generating plant, which can be located to obtain the most advantage from the standpoint of coal and water supplies.

Each addition to the fundamental of the electric system was made because of distance and load increases, and each addition brought new problems with it. The greatest program of research and development ever known has been the result. Expansion and extension of the system bring new problems because of the necessity of coordination between the various parts.

The past few years have brought about still another requirement which has accompanied the new uses that are being made of electricity. During the early years of development, the electricity that went into the buildings was used mostly to light lamps; therefore if service was off for several hours before noon or during the day, the customers did not say much about it. Today, people have other appliances besides lights, such as refrigerators, radios, sweepers, and clocks, that depend on electricity. If electric service fails for an hour or two on a summer day, it may result in loss of food in a refrigerator. Certainly, if the radio is off during a favorite program or the electric clock stops, there is inconvenience to the customers. This change in equipment has produced a change in the picture from the service standpoint, so that the development of protective devices has become increasingly important.

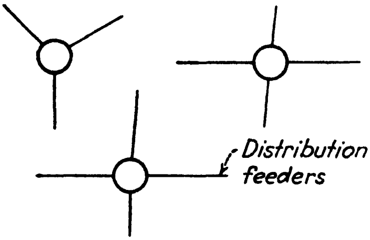


FIG. 6.—Three generating plants, each to serve its load area.

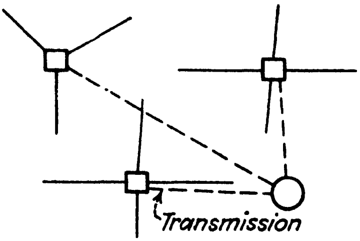


FIG. 7.—Three substations to serve the load areas, with generation at a central power plant.

Another point is that economics has played an all-important part in the development of the system, just as invention and engineering have. If it were more economical for power companies to locate power plants in each of the suburbs and haul their coal there, they would do so. But, as coal and water are of prime importance, the plants are located near a river or a lake, and near railroad or other bulk transportation facilities. This procedure is found to be justified on a cost and economy basis even though it necessitates additional transmission lines and substation equipment. Every piece of equipment on the system has justified itself on an economic basis, after it has been made possible from an engineering and manufacturing standpoint.

Many pieces of equipment and methods of distribution have been worked out and tried to a limited extent, later to be dropped or to be continued only under certain conditions. The final test for every one of these additions and developments has been and must be: "What has this to do with delivering a continuous, steady, economical supply of electrical energy to the point of consumption?"

DIVISIONS OF THE ELECTRIC SYSTEM

Fundamentally, the electric system of today is the same as it was originally. We still have generation and distribution, but to the distribution have been added the higher voltage bulk supply transmission lines and the distribution substations. In general, electric systems have these four principal divisions: generation, transmission, substations, distribution. There are many variations of this general plan, and, although it is typical, the dividing lines are not always sharp and definite.

There may be distribution services from transmission circuits, as well as transmission to a bulk supply point over lines that are nominally distribution. The area substation may be dispensed with, and a network used instead of the radial feeders. Ordinarily in urban systems, transmission from generating plants to substations is at the generating voltage, so that the step-up and step-down transformers are not required. Keeping the outline of Fig. 8 in mind will help, however, in understanding the general plan as well as the exceptions.

1. *Generation* is the conversion of mechanical energy into electrical energy. The prime power may be steam, with coal, gas, or oil as fuel, or it may be the potential energy of falling water. The generating plants are located, for economic reasons, near fuel and water supplies.

2. *Transmission* lines or cables carry the power from the generating plants to centrally located distribution substations, or load areas.

3. *Distribution substations* at the load center locations serve as the hub for radiating feeders and secondary transmission lines. Voltage step-down transformers, oil circuit breakers, voltage

regulators, and their auxiliary equipment form the starting point for the general distribution.

4. *Distribution feeders* carry the energy to the consumer's wiring. They include overhead and underground circuits, distribution and power transformers, customer substations, metering equipment, and street lighting circuits.

Parallel divisions can be noted in this outline and in the general manufacturing and distribution industries. We can think of the generating plant as our factory; our transmission lines as transportation or railroads; our substations as the warehouses; and our distribution lines, transformers, and secondaries as the retail stores and delivery trucks.

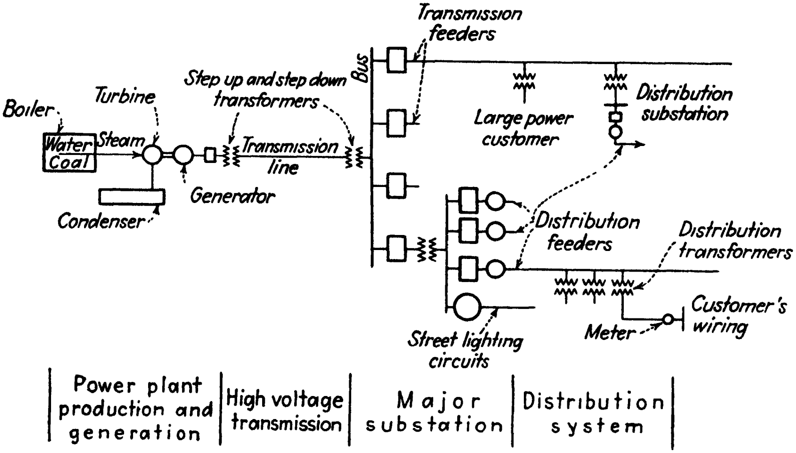


FIG. 8.—Divisions of typical electric system.

In addition to having parallel and similar divisions, the growth has been along similar lines. Many years ago it was common for each family or each neighborhood to be self-sufficient, supplying its own needs and requirements for food, housing, clothing, and other essentials. Gradually this system was replaced by one of a certain specialization in which one man became more proficient at making shoes; another at carpentry; another at plumbing; etc. Through the further working of this principle, we now have still further specialization, and our manufactured goods are supplied from large factories which are specially equipped for a given product and are so located that they have essential transportation facilities and connection with the raw materials that they use.

It is conceivable that we might have a shoe factory, a furniture factory, and factories for other things that we use in each suburb or each small town. For most of our industries, however, it has been found more satisfactory and economical to carry on these manufacturing processes in larger units, even though to the cost of the manufactured goods must be added the cost of transportation and distribution over wide areas. From these factories, the finished products are transported by railroads, boats, or trucks to warehouses or other distributing centers. From these centers, the goods are carried to retail stores and from them delivery is made to the homes of the consumers.

Needless to say, the cost of shoes plus transportation from a large factory must be less than the cost of manufacture in a small neighborhood factory, or else economic conditions would cause a change to the latter system. Similarly, electric generation and distribution from large plants and over large systems must be more economical than having several generating plants from which distribution in local areas is maintained. We must balance the cost of generation, transmission, and substations against the cost of generating at the proposed substation location.

In other words, the fact that we may have found it more economical to generate in one plant in a city, instead of having several plants in the same city, does not mean that it is cheaper to generate in one plant and transmit to several cities rather than to have a plant in each. It is well to keep in mind that the plan of an electric supply system is the result of economic comparisons, and the divisions as we know them are the result of lower investment and operating costs which are made possible by them.

In the similarity of the electric system to the general manufacturing system, we should, however, note *one very sharp contrast.* The manufacturer anticipates the future needs for his goods and builds in advance goods that are stored until called for by the retailer or customer requirements. *Electricity is not stored* but is made at the instant that it is required. The customer snaps a switch, and his order is flashed back through the distribution system, which is our retail outlet; the substation, which is our warehouse; the transmission line, which is our bulk transportation; to the generator, which is our factory—and delivery is made before he can get his hand away from the switch.

It is particularly interesting to note that the research devoted to technical problems of transmission and distribution has kept pace with the economic problems. Although distribution on the original lines was limited to at most a mile and later by development of the transformer to a number of miles, the technical limitations on distance of transmission are now in most cases in excess of the economic limitations. Today, with the equipment available, the limit of voltage and distance is based on consideration of the cost and the power to be transmitted, and not on whether it can be done technically.

SUMMARY

In this chapter, we have noted that electric distribution carries electricity from the generating plant to the homes and places of business of our customers. Starting from scratch, even within the lifetime of many men still in the business, electric supply has grown to be an absolutely essential part of our economic system and of our daily living. With transformers as the central and basic technical development in the growth from the original system, technical research and development have kept pace with the economic possibilities for extension of the service areas.

Although our generation and distribution have much in common with other manufacturing services, there is a fundamental difference in them, because of the requirement for continuous supply with no chance to anticipate demand and store up a supply of our product. It is this difference that gives to our work a part of its fascination and appeal—the feeling that the lamps must be kept burning and the lines must be kept clear.

CHAPTER II

DISTRIBUTION TO SERVE THE LOAD

Electricity, like any other manufactured product, service, or commodity, is purchased by customers to perform certain services and to fill definite wants and desires. It has been, and is, in competition with other means for performing the services, and it has had to serve better and more economically to attain its present place in our everyday living. It will undoubtedly continue in this competitive relation with other products and many yet to be developed.

This idea may be new to many of us because we have seen electricity so universally used for lighting in homes, stores, factories, and on the streets. We see the many appliances in homes, the machinery run by electric motors in factories; in fact, almost countless points seem to indicate that electricity has practically a monopoly in its field. Although it is true that no modern home owner would omit wiring his house for electric lights and appliances, we can recall that gas lights and oil lamps were displaced in competition with electric lamps. Gas, gasoline, oil, and steam can, and often do, furnish power.

In the sense that public convenience and economy have led to one, or sometimes two, distribution systems in an area or city, the service is a monopoly. The economic, governmental, and regulatory angles of this subject are outside the scope of our discussion of distribution. The point here is that although we do not have the confusion and waste that would result from several sets of lines, poles, and equipment that would be a part of general competition between companies operating in the same neighborhood, we do have competitive forces at work.

Growth of electric distribution and addition of load that is essential to our continued construction and improvement of the system are dependent on our continued meeting of these competitive forces. It is of fundamental importance that we should know our product, know what it will do, and know what our customers expect of it. Public interest in electric service has greatly increased in the past few years. It has often been the subject of front page news in our daily papers, but it is still very little understood by the vast majority of our customers.

We might sum up these few paragraphs with the observation that generation, transmission, and distribution of electricity comprise a business requiring, just as does any other manufacturing, transportation, and retail business, an analysis of the market and of the uses of the product, as well as of means and methods to promote its further acceptance and usefulness. There is no magic in these developments, and there is much more to it than building a dam to harness the power of a river, even though that part may perhaps appeal more to the imagination.

DISTRIBUTION LOADS

We have noted that electric distribution is the division of an electric system that carries electrical energy to the customers' loads. Growth, planning, and extensions of the electric system must start at the load and work back to the generators, which is in reverse order to the actual flow of the energy from the generators through the divisions of the system. In fact, economical operation of the generating plant itself depends largely on the characteristics of the load served by the distribution system being supplied from the generating plant.

There are three general classes of service and also three general classes of loads. Although there are no strict lines of separation between many of the characteristics of services to these groups and load types, it is convenient to have some such classification in mind. The general classes of load are: light, power, and heat. The general classes of service are: residential, industrial, and commercial. For a large metropolitan system, a typical numerical division of customers is: 85 per cent residential, 12 per cent commercial, and 3 per cent industrial. Of the total kilowatt-hours sold, however, the industrial customers may use 60 to 75 per cent, whereas the residential and commercial groups each account for 10 to 20 per cent.

Light.—Practically every customer of the electric system uses electricity for lighting. Formerly, lighting formed the largest part of the residential load and, in fact, nearly the whole load for many years, although it is now in second place compared with appliances. Lighting forms the predominant load used for commercial purposes, such as stores and schools. Municipal and street lighting are also included in this grouping. Lighting in industrial services is usually incidental and only a small part of what the total power requirements are.

General illumination, reading, desk and floor lamps, decorative lighting, signs, and street lighting have greatly increased the usefulness of electric service. More recently, street traffic control has been developed with electric lights, and buildings and athletic fields have been floodlighted. Many special applications of lighting, moving pictures, photography, medical apparatus, and others, have been developed. Not only has the scope of electric lighting increased, but at the same time the developments have greatly decreased the cost and increased the efficiency of the lamps.

Incandescent lamps are the most commonly used, in standard sizes from 10 to 1,000 watts, and usually for operation at either 115 or 120 volts. Other types include mercury-arc lamps for factory illumination, neon tubes for signs, fluorescent lamps for commercial use, and special lamps for equipment application.

Power.—A very large proportion of the power used in this country is furnished by electric motors, and, likewise, power requirements form a very large part of electric service kilowatt-hours sold. Motor-driven appliances have greatly increased in commercial and residential service also, principally through the use of mechanically operated refrigerators, vacuum sweepers, mixers, and other small appliances, as well as for water pumping, blowers on furnaces and heating plants, etc.

By far the largest part of power requirements is furnished by alternating current motors of the induction type. Synchronous motors are used to some extent, in larger sizes. Direct current motors are used where accurate speed control is desired, especially for street railway cars. Usually in these cases, the direct current is supplied through rotary-converter or motor-generator equipment supplied from alternating current distribution.

Induction motors have the advantage, compared with synchronous and direct current motors, of lower investment and maintenance cost, easier starting, and no brush trouble. Their disadvantages are low power factor and some decrease in speed with increase in load. Synchronous motors have the advantage of constant speed, high power factor, and higher efficiency.

A very important new field for electricity is air conditioning. We are familiar with its use in railroad cars, theaters, and office buildings but have given less thought to its general use in residential buildings. Whether it includes year-round complete air conditioning or only forced circulation of filtered, humidified air from the present heating plant, it is a potential electric load builder of considerable importance.

Power loads on the electric system present a number of special problems from the standpoint of service requirements. This is particularly true when individual motors are large compared with the total load on the service. For this reason, certain limitations are usually necessary on the permissible starting currents of motors to prevent voltage fluctuations and resulting "dips" or flickering of lights served by the same lines. The wide use of refrigerators has greatly increased the scope of this problem, and the general use of air conditioning units has required and probably will continue to require special attention. This subject is discussed in Chap. X, Voltage Control.

Heat.—Small heating appliances form a part of nearly all residence load. They include flatirons, toasters, small space heaters, percolators, and a large variety of similar devices. Electric ranges are an important and steadily increasing load, and where they are used, water heaters are also gaining in favor. Availability of gas in many areas is a large competitive factor in the possible extension of these two applications of electric service.

Electric heating is used extensively in industrial apparatus. Oven-type electric heaters for heat-treating, enameling, and baking are advantageous because of the accurate temperature control possible. Furnaces using carbon arcs are used for melting steel and brass alloy. An advantage of electric heat for this purpose is the accurate chemical control possible.

Resistance welding equipment is extensively used in sheet metal work and is increasing quite rapidly in applications such as automobile body building, as well as for all types of metal frames, boxes, etc. The pieces to be welded are pressed together by means of two electrodes, and a high current is passed through them, applied by the electrodes. This high current is passed only momentarily, during timing cycles usually measured in fractions of a second. Welding equipment of this type introduces special voltage control problems, similar to those of motor starting, when the welder is a relatively large part of the total load.

Residential or Domestic Service.—When electric service was first made generally available for home use, lighting was practically the only load. Washing and ironing were the first general appliance uses, but during more recent years a steady and continuous development has expanded the field of usefulness of service in the home. Today, an average condition is that about one-half or more of the residential consumption is for appliances and the rest for light. And the use of lighting has also greatly increased during the same time.

In addition to the larger appliances—ironers, refrigerators, radios, heating and cooking appliances, etc.—there are many other uses for electric service—clocks, razors, hair dryers, etc. Many of these use very small quantities of electrical energy, but their convenience and service have assisted in greatly increasing the public appreciation of electricity.

Expansion in this class of service will continue with further increase in the saturation of appliances, as well as a still greater use of lighting. Although many appliances are already widely used, there are others that are used in only a small percentage of the homes. Among these are ranges, water heaters, and ventilating and air conditioning units for both summer and winter use.

Wiring—the distribution system on the load side of the meter—has lagged behind in this growth. This has been a natural consequence of rapid acceptance of merchandising of these appliances, since the individual home owner has been able to use the new refrigerator, radio, or other appliance by adding an extension cord to the wiring. Houses were originally wired for a light in each room, and with only a few convenience outlets. Closely spaced outlets along all walls, lights in cupboards, halls, etc., and multiple control switches for lights are conveniences that, with ample wiring circuits and capacity, are a part of adequate wiring plans. General interest and acceptance on the part of the builders, architects, and home owners are important in the broad picture of electric distribution growth.

Industrial Service.—The predominant load in industrial services is power for motor drive. Electric heating is used extensively in metal working plants, and welding is growing in importance. We have noted that many of these loads introduce special problems for the electric system; for the power factor and starting currents of motors and the heavy momentary currents of welders affect service to other loads on the distribution lines, unless all the factors are controlled or taken into account in the layout and design.

In factories and mills, direct drive from steam engines or water wheels to long line shafts to operate machinery has been largely replaced by more flexible and more economical individual electric motor drive. Electric distribution within these plants is an important part of their operation, to carry service from a central supply point to all parts of the plant. This sometimes requires high-voltage lines and transformer installations and always necessitates distribution fuse and switch centers. In some plants, the line and equipment requirements parallel in layout and size a substation and feeder system for a town, and the distribution problems are similar.

Frequently, industrial plants have generating equipment for their own supply. Economic comparisons, especially where large amounts of steam are required in the manufacturing processes, may indicate that this method rather than purchase from the utility central station distribution system is desirable. There are cases, also, where an interconnection is possible, to give an economical balance between generation and purchase of electric power for the plant's requirements.

Electric service and its general distribution have played a large part in industrial development. By making power available at any location in a city or its surrounding territory, the distribution lines have helped in decentralizing industrial plants, thus permitting them to be located over wider areas and in locations more suitable for improved working conditions. Smoke elimination, plant cleanliness, appearance, and surroundings are other factors that have been helped.

Commercial Service.—Loads in stores, office buildings, schools, retail repair shops, meeting halls, theaters, etc., are commonly classed as commercial. Characteristics of the loads and of the service facilities required combine many of the features of both industrial and residential services. Lighting load has predominated, but refrigeration, incidental power, ventilation, and, more recently, air conditioning have steadily increased.

In general, the main business areas of the larger cities are served by a separate feeder system or by a network combining distribution at high voltages and at utilization voltages. Commercial loads in suburban and town areas are generally served from the same distribution feeders that supply the surrounding residential area.

Street lighting is a special type of load and service that requires separate feeder supply and control. In some systems, these lights are served by the general distribution feeders, but with a separate control circuit, or relays. These circuits and supply methods are considered in a later chapter.

Although the two classes of service can be considered together in the usual distribution plans, commercial and municipal loads are generally separated in the rate and accounting considerations. This is particularly true of street lighting, which requires special treatment in the economic plans as well as in the service and operating requirements

MEASURES OF LOADS

Electricity is measured in watts of demand or load and watt-hours consumed or used. These units are universally applied in expressing quantities of electrical power and energy used or required for loads and services and in measuring the quantities sold. They are considered in more detail in Chap. V.

At this point, it may be well to refer to the term **kilo,** or k., which is an important abbreviation in electrical ratings. It is from the Greek and means 1,000. Thus, 1 kv. means 1,000 volts; 5 kva. means 5,000 volt-amperes; 10 kw. is 10,000 watts; and 100 kw.-hr. is 100,000 watt-hours.

The unit of electrical power is the **watt** or, in more general use, the **kilowatt,** kw., 1,000 watts. Electrical power of 746 watts is equal to one mechanical horsepower.

The unit of electrical power consumption or use is the **kilowatt-hour,** kw.-hr., which is the equivalent of one kilowatt used for one hour. The same consumption is registered on the meter when two kilowatts are used for one-half hour and nothing is used during the next half-hour period. In the first case, the demand is 1 kw., and, in the second case, the demand is 2 kw.

Demand is defined as the load drawn from the source of supply averaged over a suitable length of time. The time period used must be known when considering demand figures. Usually the demand registered on meters for billing purposes is an average over a fifteen- or thirty-minute period. Instantaneous demand for a given load may be several times as great as this average demand, owing to starting currents of motors, etc. The usual time intervals for demand measurement are shown in Fig. 9.

Maximum demand is the highest of the demands registered or measured over a period. The measurement or approximation of this figure is very important from the service standpoint, because it determines the capacity of transformers, conductors, etc., required for that load.

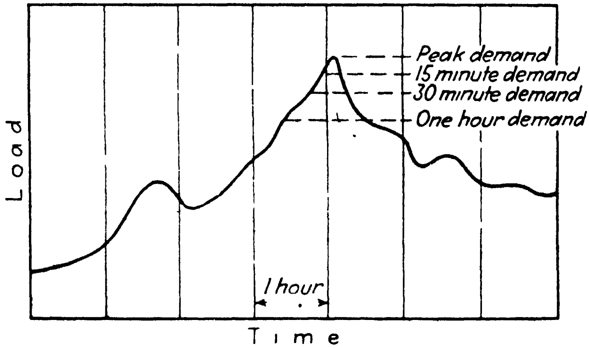


FIG. 9.—Demand is the load measured over a certain length of time. Maximum demand may be any one of these, and the time interval should be stated.

These two units of electric service, kilowatts and kilowatt-hours, are sometimes confused. When you speak of an automobile going 35 miles per hour, you must also add that the automobile was driven 1 hr., to give an idea of the distance traveled. In their respective fields, horsepower, miles per hour, and kilowatts are equivalent. To describe the work done, it is then necessary to give the length of time over which this power was used. Where the rate of power varies, the maximum demand is also of importance; it is equivalent to the highest speed that an automobile might travel. Thus, we might say that a plant had a maximum demand of 35 kw., which would be the same as another description in which we said that an automobile traveled at a maximum speed of 35 miles per hour.

Connected load is the total of the rated capacities of all electrical appliances, lamps, motors, etc., that are connected to the wiring of a particular service. The actual demand in nearly all cases is considerably less than the connected load; for different pieces of apparatus are used at different times, or some units of apparatus may not be loaded to full capacity at the same time that other units are.

Diversity is the result of this variation in the time of the use, or of the maximum use, of the connected loads. Diversity is one of the most important fundamental characteristics of electric system load and one of the bases of electric system economics. For a particular load, this diversity means that a plant with a total connected load of 150 kw. may have a maximum demand of only 100 kw. Such diversity also applies to the customers. Thus, one customer may have a maximum operating period in the morning and another in the afternoon, so that, although each of them may have a 100-kw. demand, the total demand on the system for the two may not exceed 150 kw.

Demand factor is a convenient form for expressing the relationship between connected load and demand. For example, ten 10-hp. motors on one service may have an actual demand of only 50 hp., instead of 100 hp. In this case, the demand factor is equal to 50 divided by 100, or one-half, or 50 per cent. Demand factor is defined as the ratio of maximum demand to connected load.

Demand factors vary widely for different types of load and services and are determined by averaging a large number of loads of each class. Some typical demand factors are: bakeries 55 per cent, offices 65 per cent, machine shops 65 per cent, paper mills 75 per cent, and stores 50 to 75 per cent. Determination and proper use of demand factors are very important in distribution, since it is the known connected load and the expected demand factor that determine the size of transformer installed for a particular service.

Load factor is a related characteristic. It is expressed as the ratio of the average load for a certain period of time to the maximum demand for a short interval. For example, a load may have a maximum demand of 200 kw. during the starting period in the morning. The demand may reduce during the remainder of the day and drop to a low value at 4 P.M. During a 24-hr. period, the plant may use 1,200 kw.-hr. The average load used is: 1,200 kw.-hr. divided by 24 hr., or 50 kw.; and the load factor is 50 divided by 200, or 25 per cent.

Power factor is another important value in load consideration and measurement. It expresses the relationship between the watts of the load and the product of volts and amperes actually carried on the lines. The usual meters for registering consumption of energy by customers' loads measure in watts, giving kilowatt-hours. To obtain volt-amperes, separate measurement is necessary, with a voltmeter and an ammeter to obtain volts and amperes. There are special metering arrangements to register volt-amperes directly, but they are not widely used because of their much greater cost.

Power factor is defined as the ratio of watts to volt-amperes: that is, power factor equals watts divided by volt-amperes, or kw. divided by kva. From the definition, kva. equals kw. divided by power factor. For example, a 1,000-watt load has a power factor of 80 per cent. The volt-ampere load is 1,000 divided by 0.80 equals 1,250 volt-amperes.

As most power loads have power factors of even less than 80 per cent, it is apparent that this factor must be taken into consideration in distribution layouts. Lighting and resistance heating loads are essentially at unity, or 100 per cent power factor. The technical reasons for power factor and a more complete explanation are included in Chap. VI.

System load characteristics are considered in the same manner as for the individual loads. Characteristics of the load on particular feeders, or supplied from a substation, and the total as supplied from the generating plant are each of importance in considering facilities and expansion proposals for that load area. Figure 10 shows the variation of daily load curves for Tuesday and Saturday, in winter and in summer, for an average metropolitan system.

A fundamental of central station electric distribution, based on diversity between loads, is illustrated in the following simple example. The load requirements at each hour of the day, as they might be for a street railway supply, are shown in Fig. 11. The generating plant for this load would have a maximum demand at about 7 A.M. and again at 5 P.M. Near by, there is a factory with high load period that starts at 7:30 A.M. and runs

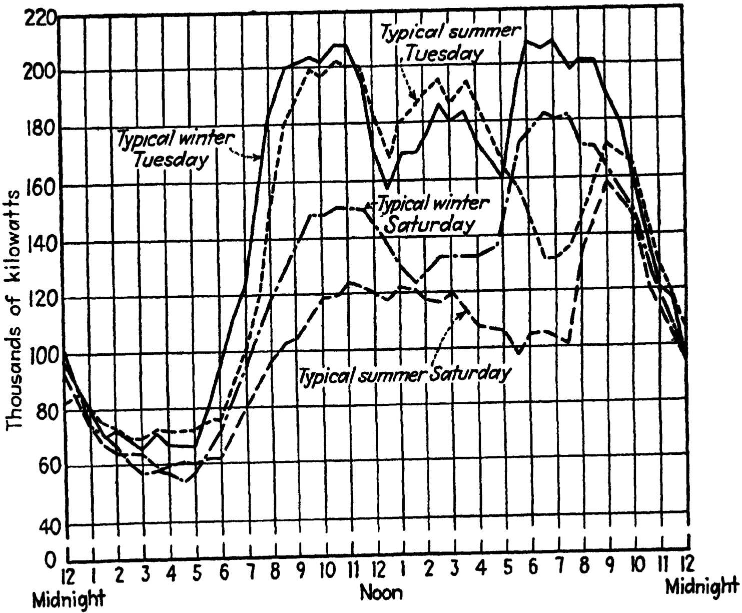


FIG. 10.—Typical load curves for a metropolitan system.

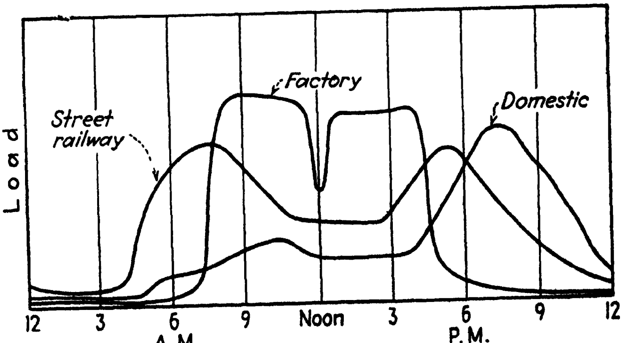


FIG. 11.—To illustrate diversity between loads of various classes. One generating plant can supply all three, with much less capacity than would be required for the total if each had separate generation.

through, except at noon, until about 4:30 P.M. In the homes of the workers of this factory, the lighting load reaches its maximum between 7:30 and 9 P.M. Owing to diversity between these loads, one power plant can furnish all three with much less capacity than the total if each has its own generation.

An opposite extreme would be an isolated plant for domestic lighting service only. Thus, a demand of 100 kw. might be required for 3 hr. per day, and there would be a low load demand the remaining 21 hr. of the day. If, however, another near-by load could be connected for a different 3-hr. period, the investment charges could be divided between the two loads. This also explains the importance of appliance use in addition to lighting in residential service, since this load spreads the use of the feeder, transformer, and secondary investment over a longer period of time. This increase technically produces an improvement of the load factor.

An analogy with another commercial example may help in understanding the meaning of diversity and demand and load factors. Suppose that a grocery store has facilities to serve 50 customers per hour and the store is open 10 hr. per day. The experience in this store indicates, however, that they can expect only one period during the day when the capacity to serve customers will be used to a maximum, and then they have 40 customers during 1 hr. During the day, they serve 200 customers.

In this analogy, the "maximum demand" is 40 customers, and 40 divided by 50, or 80 per cent, is analogous to the "demand factor." During the 10 hr., an average of 20 customers per hour is served. The "load factor" is then 20 divided by 40, or 50 per cent. The importance of diversity is apparent here also—not all the 200 customers can be served in 1 hr. And the advantages of a high "load factor" are apparent too—if it could be raised to 100 per cent, it would mean 400 customers during the day.

FLUCTUATION IN DEMAND AND CONSUMPTION

To an extent that is probably much greater than commonly realized, factors beyond our control cause variation in load on the electric system. Sales and commercial activity and general interest of the public combine to increase dependence on the electric service. This is reflected in the additional use of appliances and electric drive and application for new uses of electricity in the home, store, and factory. There are, however, three factors that greatly influence the use of this equipment after it is installed. These three factors are: general business conditions; weather conditions as they affect light intensity; and weather conditions as measured in temperature.

General business conditions affect the electric system load through industrial demand and consumption more than they do in the commercial and residential fields of application. The business depression starting in 1930 gave us a good, even if unwelcome, chance to study the effects of all business on the electric system. The largest factor of influence was the decrease in industrial and manufacturing activities, and it was reflected both in the consumption, or use of equipment already installed, and in the growth of new factories and additional equipment.

Factories that run part time, or run only part of their equipment during the usual working hours, may cut both their demand and consumption of electrical energy to half or less of the normal amount that would be used if they were running their normal rate. Improvement in business means that these factories will go back to the normal working time and add to their force of employees, thus building up the use of machinery and the demand. Experience seems to indicate that a further improvement in business first results in an increase in consumption, with a later increase in connected load and the general demand. During a period of business improvement, factory extensions and new machinery and equipment installations require new line extensions and transformer installations, thus bringing about an expansion of the distribution system.

In the residential and commercial load groups, there is very much less fluctuation of load due to general business conditions. Throughout the years following 1930, there was a continued and general increase in both the demand and consumption of both these loads, due to the increased use of refrigerators and other appliances. In the commercial field, air conditioning played a large part in this growth. A general interest in better lighting also marked this period and had a large effect in the load growth.

Weather Conditions.—These large sources of growth of electric service are appliances for the purpose of controlling weather conditions, in a limited space. It follows naturally that outside weather conditions will affect to a large extent the amount of operation required of them. We all realize that on a dark day the load should increase because there will be more lights in use.

Just how much this can influence the electric system load may not be realized, however. Because we work and live in buildings in which the light and the temperature are under control, we sometimes forget how difficult, or even impossible, it would be to continue operation of a machine or work at a desk without the assistance of electricity. For those of us who work outside on line construction and maintenance, the idea of the effect of weather conditions on our work is not so new as for those of us who are ordinarily inside.

The influence of temperature on the system load has been increased by the great increase in the use of refrigerators and, more recently, in the use of air conditioning. This effect can be so great that the load statistics for the entire system are affected. Load studies indicate that the summer temperature must be taken into account when load trends and general load forecasts are being made. For example, on one average metropolitan system, with a peak load somewhat over 220,000 kw., it was estimated that there was a maximum possible difference of 18,000 to 20,000 kw. due to differences in temperature. From this study, it appeared that the system peaks in the summer of 1937 would have been about 12,000 to 15,000 kw. higher than they actually were, if the temperatures of 1936 had prevailed in 1937. The conclusion was that there is, within certain limits, a 1,000-kw. variation in system demand for each degree variation in temperature.

The effect of temperature on the residential distribution feeders is even more pronounced. The reason for this is apparent when we remember that the amount of time that the refrigerator runs depends on the general temperature. When a great many refrigerators are considered as a group, then, the diversity among them will vary with the temperature. For example, we might consider a group of 1,000 refrigerators. On a very hot day, 800 of them may be operating together; and on a cooler day only 500 of them may be operating at one time, meaning that each of them is operating only about half of the time.

Light intensity variation has a larger and sharper effect on the load than has temperature, and this influence is felt not only in the summer, but in other seasons as well. The maximum variation in load during the day, due to light intensity, may be as much as 40,000 kw. on a system with 220,000 kw. peak demand. Light intensity has a sharper effect than temperature, for it may vary more widely during any one day. It also affects residential load relatively more than it does industrial and commercial loads.

DISTRIBUTION LOAD STUDY

To be sure that the distribution facilities and capacities are adequate to serve the loads and to meet new demands as they are added, it is necessary continually to check and study data of not only the present loading, but also the trends. Large increases in individual industrial loads, and to some extent the larger commercial increases, are made known ahead of the time of their addition. But it is not only impractical, but also physically impossible, to know of all of the small increases made by the thousands of customers served by a large distribution system. It is, therefore, necessary to have a definite program of load study and testing.

Transformer Load.—Checking and testing of transformer loads are usually a continuous part of operation on a large system, a check progressing over all the transformers every one or two years. Smaller systems may be covered in a shorter time, and the survey can be made periodically. Distribution transformers are the smallest capacity units in the circuit of supply to the customers and are, therefore, proportionally most affected by individual load increases. Not only their size but also their location are important in the adequate supply, continuity of service, and control of voltage to the customers' services. This subject is considered in detail in Chap. VIII.

Feeder Loading.—All the factors that are present in the general system load studies are also present in consideration of the individual distribution feeders. Diversity between loads and the demands of the loads are indicated directly in the demand figures, or current readings for each feeder. Under present economic and load growth conditions, it is essential that all these data, together with the transformer readings and regulator and substation equipment ratings, should be tabulated periodically. Plans can then be made for the rearrangement of feeders and the addition of new ones as required.

General System Data.—By using the feeder loading data, groups of feeders, districts, and geographical divisions can be studied for system planning of major rearrangements, expansion, and new construction. Upon this basis, future distribution substation locations, new feeder areas, and, in turn, transmission lines to serve substations can be planned. *Load density* is a factor that may be considered at this point. It is useful principally for the comparison of areas or system districts. It may be given in terms of connected transformer capacity or in actual simultaneous demand per square mile. For smaller areas and for individual feeders, the kilovolt-amperes per thousand feet or per mile is often more convenient to use.

For example, high load density districts, such as the downtown office section of cities, have 10,000 kva. per square mile and higher. Around the edge of these districts, load densities may vary from 2,500 to 7,500 kva. per square mile. Urban feeders may vary from 1,000 to 2,500 kva., and suburban feeders from a few hundred to 1,000 or 2,500 kva. per square mile. Rural lines often have as low as 5 kva. per square mile connected, with three to five customers per mile of line along the road, and 100 kva. per square mile would be high.

Forecasting of load growth is to some extent possible, and it is necessary for the larger parts of the system. As new feeders, substations, and transmission lines require advance planning for construction, anticipation of load is essential. This is particularly true for major additions, where one to two years may be needed for layout, delivery of equipment, and construction.

Although extension of electric service lines into new territory has in the past accounted for a large part of the growth of the electric system load, less can be expected from this source in the future. Except for the more remote rural areas, service is now available in all parts of the United States, and new extensions of the service area are limited to the rural lines. Feeders will be extended into new residential subdivisions in suburban areas, and new lines will be needed for industrial loads; but the conclusion must be drawn that future growth by reaching entirely new loads and areas is definitely limited.

Summing up the statistics available, however, leads to the conclusion that a great amount of future growth in load is probable from the standpoint of density in the areas now served. Wider use of appliances now available, new developments, and more use of lighting for utility and decorative purposes will increase the load on secondaries, transformers, feeders, and substations, and make increasing capacity necessary. For the distribution system, this means that rebuilding, additions, and rearrangement work is the major program, rather than additional mileage of line construction.

Saturation of Appliances.—That there is plenty of chance for growth of load through increases in appliance load may be seen from the figures of Table I, for an average metropolitan system. The figures show the percentage of total residential customers that have the appliance. The average consumption shown is estimated kilowatt-hours per appliance per year. Most of these data are, of necessity, based largely on estimates, which are checked from merchandise sales figures, spot or sampling surveys, load tests, and general information.

TABLE I.—SATURATION AND USE OF APPLIANCES

Appliance	Saturation, per cent	Kw.-hr. per year	Appliance	Saturation, per cent	Kw.-hr. per year
Refrigerator.....	60	400	Range... ...	2	1,000
Radio	85	80	Water heater. .	0.5	3,700
Washer	70	42	Furnace operation	1	300
Iron	90	90	Air conditioning..	0.5	1,000

Toasters, mixers, etc., 90 per cent have at least one appliance. Average use 30 kw.-hr. Residence lighting uses 350 kw.-hr. per year average. "Better Lighting" adds 250 kw.-hr.

SUMMARY AND PROBLEMS

Consideration of loads served by the electric system covers only their general characteristics for our purpose in distribution study. Operation and planning often require much more detailed study, especially of the instantaneous or starting currents, demand, power factor, fluctuations, and load factor characteristics of both individual loads and groups. We have noted that distribution loads may be grouped as light, power, or heat and that services may be classed as residential or domestic, industrial, and commercial, with street lighting and other municipal or public uses as a separate group.

Loads on the distribution lines are measured in kilowatts and kilowatt-hours. These two measures, together with connected load, diversity, demand factor, load factor, and power factor data, are essential information in distribution planning and operation. Exact information is usually not available or necessary on some of these data, but an understanding of them and their relationships is essential in using the information that is available.

Future growth of the distribution system depends on wider use of service now available, that is, an increase in saturation of appliances and a continued dependence on electric conveniences. This, in turn, requires rearrangement and rebuilding of lines for increased capacity and at the same time increases the necessity for continuity of service and close control of voltage.

Use of electric refrigerators, radios, and electric clocks, in addition to lighting, has made even a short outage of service noticeable. The attention given to lighting conditions, together with the use of radios, has made the customers more conscious of voltage conditions as well. A continued interest in adequacy of facilities, both on the supply side of the meter and on the load or interior wiring side, is a natural result of this dependence.

The factors for measurement and comparison of load data, in this chapter, are summarized in the following examples. The reader is urged to solve the problems for his own understanding of the use and relationships of these terms.

1,000 watts used for 1 hr. = 1 kw.-hr.

Demand is the load averaged over an interval of time.

Maximum demand is the highest of the demands.

Connected load is the total of rated capacity on a service.

Demand factor equals maximum demand divided by connected load; therefore, maximum demand equals connected load multiplied by demand factor.

Load factor is average load divided by maximum demand. Average load is the total kilowatt-hours divided by the total hours of the period.

Power factor is watts divided by volt-amperes or kilowatts divided by kilovolt-amperes; therefore, kilovolt-amperes equals kilowatts divided by power factor.

Problems:

1. A voltmeter, an ammeter, and a wattmeter used in the supply to a small single-phase motor gave these readings under one condition of load: 222 volts, 27 amperes, 4,350 watts. What is the power factor of the circuit?

2. A customer is to have a connected load of 130 kw. For the class of load, it is known that the demand factor is 60 per cent and power factor 80 per cent. What is the maximum demand to be expected, and what will the kilovolt-amperes be with this demand?

3. A customer has a 200-kw. demand with a connected load of 450 hp. The connected load is to be increased to 675 hp. A power factor check shows 70 per cent P.F. What size transformer bank should be installed, assuming the same demand factor and power factor for the new load?

4. A plant with a connected load of 150 kw. had a maximum demand of 75 kw. The meter registration in seven days was 4,200 kw.-hr. What were the demand factor and the load factor?

NOTE: The answers for these problems are given in the Appendix, to enable the reader to check his own calculations

CHAPTER III

THE DISTRIBUTION DIVISION

We have considered the electric system and its divisions and some features of the loads that it serves. In this chapter will be discussed some of the fundamental features and details of the distribution division, which is the point of contact of the electric system with the loads. Also, the operating organization of the distribution division has the most frequent point of contact with the customers, serving functions parallel to retailing and delivery of our product. It may be well, therefore, to include an outline of the service and operating routine on which physical growth of this division and of the whole electric system is based.

The wide variation in load densities on the typical large electric system has been noted; as might be expected, this leads to a considerable variation in the types of construction and arrangements of the distribution system itself. Contributing to these variations are also factors of rate of growth, background, city development, and engineering individualities. Perhaps it is to be wondered that so much standardization has been obtained.

Two activities have contributed to standardization of distribution and of electric systems in general. (1) Economic reasons in equipment design and manufacture have led to voltage and frequency grouping, which has been helped by and also has helped the wide use of appliances. (2) Technical articles and engineering papers, committee and association meetings, and general interchange of reports and information have led to dissemination of conclusions and operating data on various arrangements and plans for the distribution layout.

PLANS AND CONSTRUCTION IN DISTRIBUTION

In general, there are two basic plans or systems of distribution: radial and network.

Also, there are two basic methods of construction: overhead and underground.

Two combinations of these two plans and two construction methods are in most general use—overhead radial and underground network. The other two combinations are used less extensively—overhead network and underground radial—although underground construction is often used in certain areas or sections, in conjunction with overhead radial systems.

Radial System.—The radial-type system (Fig. 12) is the simpler and the more widely used of the two. It comprises separate feeders radiating out of the substation, each supplying the area to which it is confined. From the feeder, there radiate sub-feeders or branches. The expression "radial system" also denotes that the secondaries supplied by each transformer radiate out from it and are not joined to those of the adjacent transformers. Radial circuits may be either overhead or underground, but the vast majority are overhead.

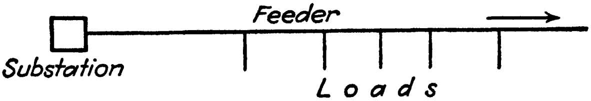


Fig. 12.—Radial system.

With radial feeders, trouble on the line, a wire down, or a fault may cause an outage to all customers supplied by that feeder. On the radial transformer and secondary mains, trouble that causes the transformer to fail or its fuse to blow will cause an outage to the customers served from that transformer. Because of the attention that has been given to the design and operation of the equipment and lines, this limitation is not serious, however, and the usual record of outages is not such that the increased investment for dual service is justified.

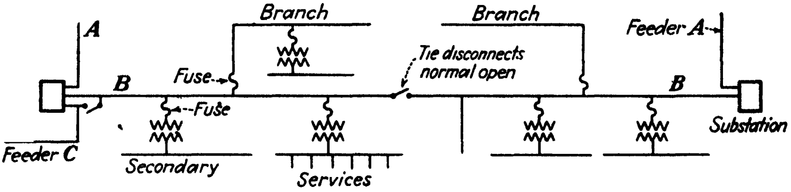


Fig. 13.—Elements of two radial feeders.

Radial circuits are usually provided with tie switches so that under emergency conditions, or with the substation supply switch open, one feeder can be supplied from another by tying the two together, as shown in Fig. 13. Sectionalizing switches may also be used to clear a section of line in trouble, from the remainder of the feeder. Fuses are often used for branch lines or taps; therefore, if they are in trouble the branch only will be out of service, and the main feeder will continue in operation.

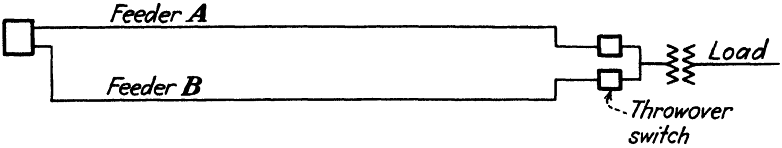


FIG. 14.—Normal and emergency supply to a customer.

Dual service from radial feeders, with loop or throw-over switching, may be supplied for load services where continuity is especially important, as for hospitals, large industrial loads, and large telephone exchanges. With throw-over switching, one line, as *A* in Fig. 14, is normally supplying the load and the other switch is open. An outage or failure of voltage on the normal supply line *A* causes its switch to open immediately and the switch on the emergency line *B* to close.

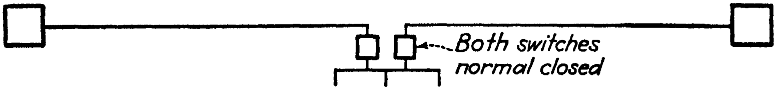


FIG. 15.—Dual service from two radial feeders, with loop switching.

With loop switching (Fig. 15), both switches are normally closed, tying the two feeders together. Trouble on either line causes its switch to open, through reverse power flow relaying, and service is continued on the remaining line. These variations of the radial system are used only to a limited extent because of cost and because they require two feeders at the same location, making feeder rearrangements for load growth more difficult. Another modification of the radial system is shown in Fig. 16.

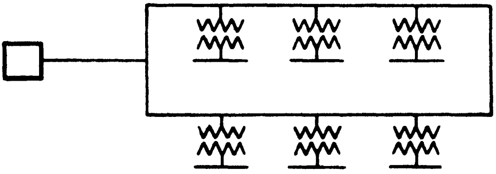


FIG. 16.—Ring primary feeder.

With the ring arrangement of primary feeder, a wire down or open at any point will still permit supply to all sections of the feeder.

Network System.—In a network system, shown in fundamental form in Fig. 17, the secondaries of two or more transformers are tied together. Adjacent transformers may be supplied from the same or different feeders, and the secondaries may have fuses, switches, or network protectors between the transformers and the network mains or grids. The majority of network systems distribute at the utilization voltage. Because the network system is usually associated with high load density, where underground construction may also be necessary, network systems and underground construction generally go together.

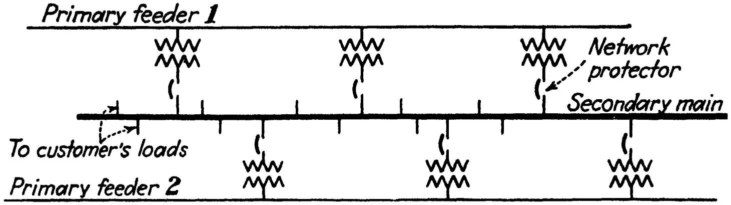


Fig. 17. Secondary network system.

Some utilities use a modified secondary network in the overhead district also. The secondaries of adjacent transformers are tied together to form a main, which parallels the primary feeder.

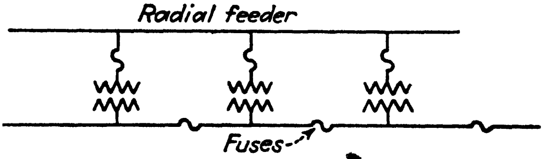


Fig. 18.—Banked secondaries (modified form of network).

Fuses, in the secondary of each transformer as well as in the primary, blow in case of transformer trouble and leave the services from this transformer supplied from the adjacent transformers. Adjacent secondary mains may also be tied together through fuses, as shown in Fig. 18. Where this is done, it is usually to reduce the drop in voltage caused by motor starting currents. The use of these arrangements has some disadvantages, as well as advantages.

One arrangement of primary network is shown in Fig. 19. The primary feeders are tied together and are supplied from network or small substation units. Transmission lines supply direct to these units, which replace the larger substations used with the primary radial system.

Overhead Construction.—Poles, crossarms, insulators, hardware, guying materials, and braid insulated or bare wire conductors, with transformers mounted on poles or platforms, constitute the chief items of construction for overhead lines. The lines are built along the streets, alleys, or highways. This type of construction has contributed to the economy of electric service, because it requires less investment than underground and is readily rearranged, extended, and expanded as the load grows. With underground, distribution costs for building and operating would be several times as great, except in the high load density areas. This, in turn, would be reflected in the cost of service and its growth.

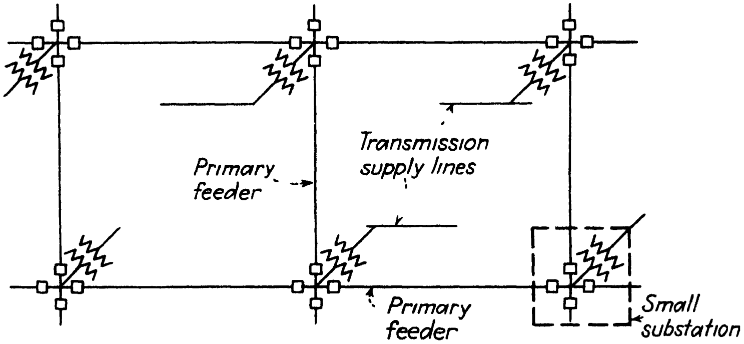


Fig. 19.— Primary network system.

Along with the electrical and circuit designs for overhead lines, there are many features of mechanical design that must be included. In the daily work of construction, application of mechanical fundamentals predominates in importance. Clearances, wire sags and tensions, guying, strengths of materials, interference of outside obstructions, and right of way are some of the features that must be considered. In addition to the electrical problems of voltage control and load carrying capacity, design for lightning protection, grounding, and fault protection must be planned.

Underground Construction.—Cables, ducts, manholes, potheads, and terminal equipment, with subway-type transformers, are the major items with which underground systems are constructed. Because the ducts must be placed permanently in a trench, usually covered with concrete and paving, the cost of additions and rearrangements is high, and the systems are not so flexible as overhead. Cable is much more expensive than open wire. However, in very high load density areas, underground construction is actually less expensive than overhead would be, because conductor sizes are large and the overhead structures would be extremely unwieldy. An additional factor is, of course, that the heavy conductors would be not only unsightly, but also difficult to handle in the congested areas of our larger cities.

The principal mechanical problems in underground construction involve clearing the obstructions, pavement, pipes, sewers, and tracks with which the duct lines must share space in the streets. Conductors may be insulated with impregnated paper, rubber, or varnished cambric, and the assembly is usually covered with lead, although nonmetallic sheaths are used to some extent. Manholes are used to provide for pulling sections of cable, for joints, and for transformer installations. Potheads are generally used at the cable ends, and their installation, together with the splicing and joints in cable, is the most important point for expert workmanship.

Overhead Radial.—The predominant part of most distribution systems is the combination of overhead construction and radial circuits, and a vast majority of the customers are served in this way. A majority of these systems operate at 4,000 or 4,160 volts, three-phase, with a neutral wire carried with the three primary phase conductors, so that the transformers can be connected for 2,300 or 2,400 volts between a phase wire and the neutral.

Originally, much of the alternating current generation was at 2,300 volts delta, and the original distribution was at the same voltage. The wide use of the 4-kv. system is probably due as much to the ease and low cost of increasing capacity by changing these 2,300-volt delta systems over to a four-wire star system as to any inherent advantages that might have warranted its adoption otherwise.

Other voltages of generation are 6,600, 12,000, and 13,200 volts. Some systems use these voltages for general distribution, but it is more common to use the higher voltage for bulk supply and step down to a lower voltage for general distribution, especially where generation is at 12 or 13.2 kv. It is common practice to serve large industrial customers from the higher voltage feeders, operating at the generation voltage. These lines also supply distribution substations, although major substations in urban areas are usually supplied by main underground cable circuits.

Underground Network.—Two factors have led to the adoption of underground networks in the central business areas of our larger cities. We have noted that underground construction is almost a necessity because of mechanical limitations, and also that it is economically justified in congested areas. The importance of absolute continuity of service to elevators in large office buildings and to theaters, large auditoriums, and stores has made the network system essential. In many of these cities, the original direct current systems were operated as a network or grid, and the change to the network for alternating current supply has been gradual and in many cases is not complete yet.

Transmission to these networks is at the generating voltage. Transformers are installed in vaults under the pavement or sidewalks or in basement space of adjacent buildings These transformers feed the secondary grid through network protectors, and services to the buildings are taken from the grid. Adjacent transformers are supplied from different transmission cables, so that a transmission outage will leave the secondary grid or main supplied from transformers on the remaining transmission circuits. When this happens, the network protectors operate to clear the grid from the transformers which are connected to the transmission circuit that is out of service.

Services available to customers are quite well standardized, and all but a few systems operate at a frequency of 60 cycles. This fact is very important for two reasons: (1) because of the inconvenience and cost that would be involved if appliances used in one city could not be moved and used in another city; (2) because of the many different ratings that would be necessary on appliances manufactured for nationwide sale.

Two general classes of service are ordinarily available to customers of electric supply systems, and a combination of the two is supplied in the network areas.

1. *Single-phase,* for lighting, small heating, and small power appliances, is available to all customers and is the basic supply in residential and commercial areas. Two basic voltages are used: 115 volts on some and 120 volts on other systems. Division between these two is almost equal, and the original 110-volt services have been almost completely superseded by either 115 or 120 volts. Lamps are manufactured for both voltages, and the correct rating should be used. Most appliances can be operated at either voltage, or at 110, as they are not so critical regarding voltage.

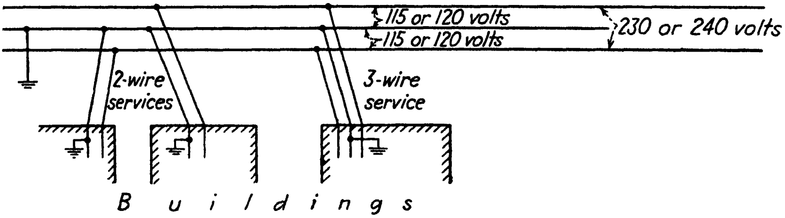


FIG. 20.—Single-phase two-wire and three-wire services from secondary main.

Distribution is generally over three-wire secondary mains, with either a two-wire or a three-wire service to each building. This three-wire system is equivalent to two two-wire circuits combined so that one wire, the neutral, serves as one wire of each of the two circuits, as shown in Fig. 20. Between the two outside wires, the voltage is 230 or 240, and the voltage on the main is indicated—115/230 volts or 120/240 volts. Larger appliances, as pumps, blowers, air conditioning, and ranges, may be operated at 230 or 240 volts, single-phase, from the same three-wire services.

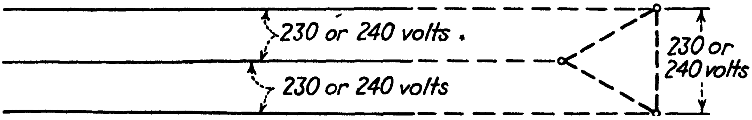


FIG. 21.—Three-phase, three-wire service.

2. *Three-phase* service is used for industrial and large power loads. These are at 230 or 240 volts, as shown in Fig. 21, or they may be at 460 or 480 volts. In some large industrial plants,

primary service at 4,000 or 4,160 volts is also used. Motors are rated at 220 or 440 volts with a permissible voltage range 10 per cent above or below the rating.

3. *Three-phase four-wire* combination power and light services are used in the network areas, to avoid the necessity of two supply, secondary, and service systems. Many customers require three-phase power for elevators, blowers, or other large equipment in addition to lighting. The neutral wire is grounded, and 120 volts is obtained between this wire and any one of the other three. For three-phase power, the three outside wires are used, giving 208 volts, which is within the 220-volt motor rating, with 10 per cent permissible variation (Fig. 22).

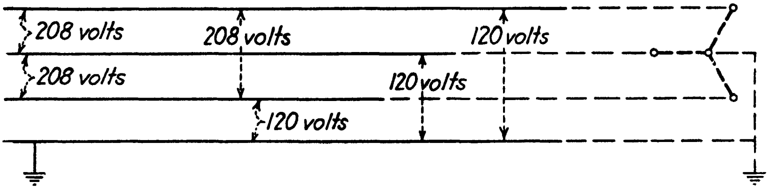


FIG. 22.—Three-phase, four-wire service.

To some extent, this three-phase four-wire system has also been extended to areas supplied by radial feeders. This is particularly true for large apartment buildings, hotels, etc., not in the central commercial area, but having similar load conditions.

A rating of 120 *volts* will be referred to, throughout the discussion, to avoid the necessity of using "115 or 120 volts," although it should be remembered that either is meant. Similarly, multiples of 120 volts will be used for the same reason—240, 480, 2,400 (and 4,160) volts.

DEVELOPMENT OF A DISTRIBUTION PLAN

A development and plan for a distribution system along the most economical and coordinated lines would logically be divided into three general topics:

Analysis of service conditions and load to be served.
Engineering plans to meet the service requirements.
Economic study of investment and operating costs of the various plans.

Seldom, however, is a distribution system laid out in this ideal way because: (1) we are always adding to or rebuilding a system that already exists; and (2) load forecasts are extremely difficult when considered over the period of years that distribution lines are in service. A great amount of study has been given to this subject of planning, to the end that distribution can grow with the load with a minimum of retirement of lines and equipment already in service. Consideration of these factors assists us in a realization of the fundamentals of design.

An analysis of the service conditions includes a study of load to be served and the density of the customers. These conditions, together with the points available for supply of the lines, determine the length and total load that is to be carried on the lines. It may be found that it would be more economical to establish additional outlying distribution substations, to place the available points of supply closer to the general area of the loads to be served. Street and road layouts and natural conditions such as topography of the country must also be considered in the distribution feeder planning.

Electrical design can be determined on the basis of allowable voltage regulation and on the load and length of line conditions. In determining wire size, it is important also to consider the addition of voltage regulating devices for control, which in turn may increase the possible length of the lines for the given conditions. Electrical design includes the application of transformers and their accessory and protective equipment. Further factors include the protection and expected operating characteristics of the line. Use of arresters, fuses, grounding, the spacing of wires and insulation values to be used, coordination of the fuses on the lines with the protection at the substation, and other points of a similar nature must be included.

Mechanical design, after the principal electrical characteristics are determined, starts with the wire size, clearances, and spacing of the wires and the resultant loading of the structure. This part of the design includes the selection of pole height and span length, the hardware and supports, guying, dead-end and clamping arrangement, and selection of hardware and materials to be used. Along with this, the life and possible operating values of various materials must be considered.

A cost comparison is then set up, based on the electrical and mechanical designs being considered. Several designs may well be made in order to obtain a comparison of the investment costs required for various span lengths, methods of voltage control, and arrangement of the system as a whole. For example, it may be found more economical to arrange additional points of supply to allow shorter lines, or it may be found advisable to increase the distribution voltage—but it must be remembered that each change also involves changes in the other principal factors of the design. Raising the voltage, although it will permit longer lines for a given load, will also increase the clearances and rating of the transformers and accessories, which may in turn increase the cost to more than would be involved were a lower voltage used for the particular conditions.

Cost per mile is reflected in the cost of service per customer. This investment is included with other items in determining the minimum cost of service, which must be covered in the customers' monthly bills regardless of the amount of energy use. These factors of design are summarized in Fig. 23. We cannot, of course, use and consider each of them for each particular line extension, but they are the fundamentals behind the system design and are important for any general study of plans. Costs and economic comparisons are discussed further in Chap. XV.

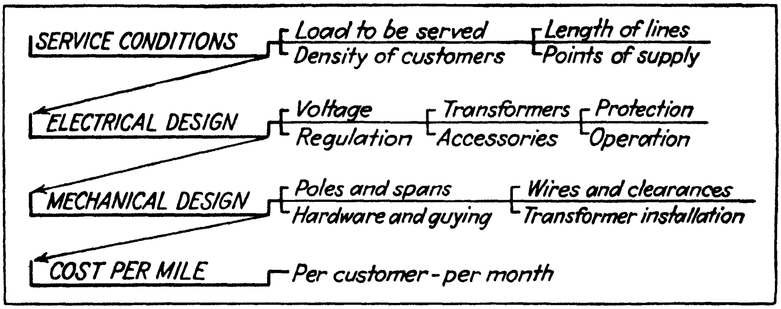


FIG. 23.—Summary of factors in distribution design.

Standardization of construction methods and materials is a very important function of distribution engineering. Where hundreds or thousands of identical or similar installations are being made, a handbook of typical drawings saves a great amount of time and expense. Pole top arrangements, guying details, transformer and other equipment installations, conductor sagging, duct and manhole construction, meter and service installations—these and many other detail layouts can be shown in general.

For a particular construction job, then, an outline drawing can show the plan and arrangement to fit the particular conditions, together with notes referring to the standard drawings. This replaces a large detail layout for each job, or the other extreme of no layout at all, which may result in great loss of time and effort on the part of the construction crew. Such standardization of methods is also essential for maintenance and operation purposes, since thus replacements and repairs can be more readily made.

Material specifications are an essential part of such standardization. Many items of hardware, dimensions, standards of quality, and performance requirements are included in the standards and specifications adopted by national associations and committees. However, there are still a number of items requiring consideration by individual operating organizations to fit in with the construction methods adopted.

Maps and records are also a necessary part of good operating practice. Although it may be possible, with a very small distribution system, to carry in one's memory essential details of the lines, where they are, the sizes of transformers and conductors, etc., this is impossible with a large system. Detail maps, showing street or road layouts, pole locations, transformer installations, and circuit arrangements are usually kept in the office. Smaller maps showing the general route and layout of feeders, junctions, switches, etc., are then made for field use. Drawings of special installations and of the arrangement and location of stations, together with lists of equipment, are kept on file in both engineering and operating offices.

GROWTH OF THE ELECTRIC DISTRIBUTION SYSTEM

As we have noted in the previous chapter, electric service is now available to all the urban and small town loads and to the rural areas surrounding the towns. Rural lines have been extended into many of the areas beyond, and it is principally in this field that entirely new construction is yet to be done. This general picture is in sharp contrast with that of the situation well within the memory of many of us, when new distribution feeders were being extended into residential suburbs and there were many streets that did not have electric service.

The future growth of the electric system will be largely as a result of increase in density in the territory now served. This means that the mileage of line will not greatly increase, but that capacity of the lines will increase, owing both to the addition of load by present customers and to the building of new houses and factories. Branch lines from the present feeders and extensions of many present branches will be constructed to reach new residential subdivisions and developments. In general, however, the largest amount of construction will be for rebuilding existing lines as they depreciate or become obsolescent, owing to the need for larger wire and heavier construction.

New construction, rearrangement, or rebuilding is made necessary by one or more of several factors:

An extension of line and transformer installation for new load or new customers.
Addition or change for additional load by a present customer.
Rearrangement for increased capacity indicated to be necessary by load study—transformer test, voltage check, feeder loading.
Addition and change of feeder arrangements as new distribution substations are required.
Addition and change for improvement of service or reliability.
Movement and rebuilding in conjunction with highway, bridge, or other improvement.

Procedure for making additions is usually along a fairly well-organized routine. Applications for service to new homes, stores, and small power loads in areas already served may be taken care of immediately by installing a service line from mains in the street. Meter and service locations are assigned by an inspector, and a service crew makes the addition.

For larger extensions, where new line and transformer installations may be necessary, more elaborate preliminaries are usually essential. Inspection of field conditions and of maps and records precedes making a preliminary layout and estimate of cost. The layout proposed is discussed with supervisors who will be responsible for its execution and later its operation. The cost estimate and a brief explanation of the reason for the expenditure are then passed for approval by the management. Issuance of a work order or job order follows, and the detail layout, drawings, lists of materials, and ordering of equipment can be carried through.

During this preliminary work, and also during the construction that follows, many other details also need consideration. Right of way or permission to locate poles or other structures or to excavate must be obtained from property owners or public authorities. Tree trimming or clearing of the route may be necessary. Construction equipment, tools, trucks, and, most important of all, the personnel and their safety, training, and coordination of effort must be included in the thought and preparations for construction and for operation and maintenance of the distribution system.

Not only must the expenditure for new construction be justified and approved, but other records must be set up as well. Metering equipment must be assigned, the contract or application must be arranged, and property and valuation records must be prepared In fact, it may be seen that actual construction of a new line is but one part, although it is the central measure, in expansion of the distribution system facilities.

SUMMARY

Distribution—delivery of electricity to the customers—must be planned to meet the conditions of the particular area and the requirements of the load Planning ahead is important, because lines and equipment represent an investment that is relatively fixed and not readily changed. They must be adaptable to load growth without excessive obsolescence. Where most other delivery systems can be expanded by adding warehouse space and trucks, electric distribution must be built up on a more permanent basis.

Overhead construction of radial feeders is the vast web for supply over a major part of the system. Underground construction is used largely for bulk transmission and for network supply to high load density areas. Underground is often used for radial feeders also, and modified network plans are used with overhead, with many variations of these fundamentals possible to meet local conditions. Load analysis, engineering plans, and economic comparisons are the bases for distribution planning. A high degree of judgment is always necessary, since, although present conditions control exact calculations, the investment must still fit conditions of several years hence.

Although these engineering studies are fundamental, the daily work of laying out extensions for system growth involves more of single circuit design, mechanical design, and adaptation of construction standards. And above all, it includes correlation of the distribution system to surrounding conditions, cooperation with customers in location of service facilities, and coordination of the numerous departments of the electric service utility. *Electric service* is much broader than *electricity supply*—it includes our personal efforts and service, over and above the layout and operation of the lines for supply.

CHAPTER IV

GENERATION OF ELECTRICITY

Many of the properties of electric circuits will be most readily understood if we have a fundamental idea of how the electrical energy is generated. Generation of electrical energy is the conversion of mechanical energy through the medium of magnetism. An electric current is generated in a conductor when the conductor is moved through a magnetic field, so as to cut magnetic lines of force. Mechanical energy is required to move the group of conductors through the magnetic field.

Mechanical energy to drive the electric generator may be supplied by a steam engine, a steam turbine, a water wheel, or an internal combustion engine using gas, gasoline, or oil as fuel. Steam turbine drive supplies the major part of the power for generating electrical energy carried over our general distribution system. Water power is second, and gas and oil engine drive are relatively less economical for large plants, their use being mostly confined to industrial or isolated plants, and not for general distribution.

Steam power plants have as principal parts boilers, fuel handling equipment, and, of great importance for the efficiency and economy of the plant, steam condensing units. Although coal is the most commonly used fuel, oil or gas may also be used under the boilers, where they are economically available. The heat of the fuel converts water to steam, which is carried to the turbines and then to the condensers, for conversion back to water, ready for another cycle of operation.

In turbines, the steam strikes against blades on a shaft, causing the shaft to rotate. By expansion, the steam liberates its heat energy and gives high velocity energy to the turbine wheel. Steam is admitted to the turbine at a high temperature and a high pressure. When the steam leaves the turbine, it is at lower pressure because it has expanded; the lower this pressure, the greater is the expansion between entering and leaving. By creating a vacuum that acts as a suction on the steam, there is an increase in pressure drop from one end of the turbine to the other, and thus more energy is extracted from the steam.

This vacuum could be created by a pump, but this would require a large amount of power. By taking advantage of another principle, it is accomplished much more efficiently. When steam condenses into water, the volume of the water is but a small fraction of the original volume of the steam. By condensing steam, we are able to produce a vacuum. Steam, after it leaves the last stage of the turbine, is directed into a large condensing well or tank. Around and through this tank or condensing well, water from a river or lake is circulated to cool the steam. The constant supply of condensing water is as important in the location of a power plant as the economical handling and supplying of coal to the plant. In fact, more water may be required through the condensing well of the power plant supplying a city than is required through the water works supplying all the needs of that city.

Water power also has a large place in the generation of electricity. Mechanically, hydroelectric plants are much less complex than are steam power plants. But where large dams must be built to hold back and store the water and to create the fall, the large investment required and the other problems to be met may offset many of the advantages that the "free power" of falling water might otherwise have.

The cost of power, where it can be used, has two main elements: cost to generate and cost to transmit, and both must be considered. In the United States, most of the cities, with some notable exceptions, have grown up at a considerable distance from the natural location of hydro development. To the investment cost of the power development must therefore be added that investment for transmission and terminal equipment.

FOUNDATION FOR ELECTRICAL DEVELOPMENT

Although it was not until Edison's work in the invention of electric lamps and in developing and starting commercial electrical generation and distribution that general practical use was made of the principles of electric current, these principles were known by scientists and experimenters about fifty years before. One of the foremost of this group of men, who laid the foundation for our present knowledge of electricity and its uses, was Michael Faraday of England. His experiments led, in 1831, to the discovery of the principle of electromagnetic induction.

Other experimenters of this period were principally interested, as was Faraday, in chemical research, particularly with galvanic apparatus. Some of their names are still used by us in electrical terminology—Volta, Ampère, Galvani, Watt, Coulomb, Oersted, Ohm, and Henry.

Almost all electrical machinery, including generators, transformers, and motors, depends on the principles of induction of current, for which the experimental foundations were laid by Faraday. In addition, Faraday originated much of the basic electrical terminology still in use. Faraday's ideas were put into mathematical form by James Maxwell. It was made clear that magnetic and electric forces are reciprocally related, since an electric current produces a magnetic field and a change in a magnetic field produces an electric force.

A study of the history of electrical experiment and development leads to an interesting observation. The foundation has been laid by the experimental work of physicists and research scientists, and the practical application has come many years later through the development and introduction of apparatus. Between these two stages, there has been much valuable work in explaining and extending the experiments, and finally in putting the results into a mathematical form that could be understood by others. The same observation is largely true in the later invention and development. Equipment was built, tested, and operated, and then mathematical principles were applied to explain and study the operation and to put the design into a form that could be applied and changed at will for later development.

GENERATION

Faraday explained some of the observations that he made in his experiments by imagining a field of magnetism or magnetic lines of force traveling freely through the space between two poles of a magnet. He observed that, when an electric conductor is moved through this magnetic field, a slight current will be induced in the conductor. In a very simple form, this is shown in Fig. 24.

There has been no change in this fundamental principle of generating electricity. The horseshoe magnet of these experiments has become the revolving element of the generator, energized from a small generator or exciter, which is mounted on the shaft with the main generator. The stationary element of the generator is made up of laminations in which are set insulated copper bars, which are the main windings of the generator and are in effect many loops replacing the single conductor in the diagram. By varying the current output of the exciter, the intensity of the magnetic field is varied, and the voltage of the main generator is controlled.

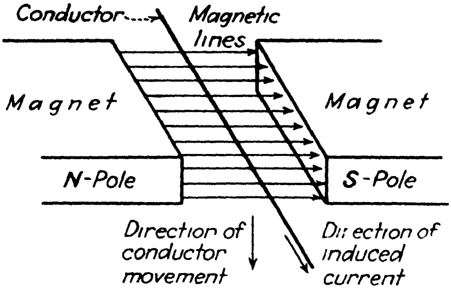


FIG. 24.—A current is generated in the conductor when it is moved through the magnetic field.

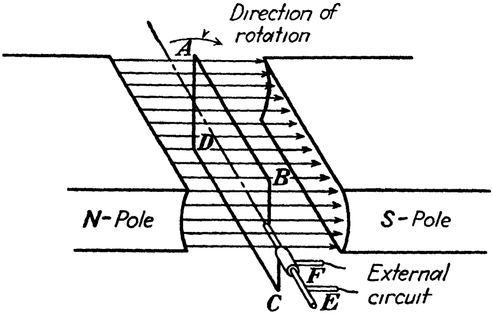


FIG. 25.—Conductor arranged in a loop to rotate in the field and supply an external circuit.

To understand what is taking place in the electric generator, we can assume a simple loop of wire which is arranged so that it can be rotated and will repeatedly cut through the magnetic field. This loop can then be connected to an external circuit and the current sent out from the generator, as in Fig. 25.

It should be noted that for one direction of conductor movement there is a corresponding direction of induced current. When the loop is in a position such that the conductor is not cutting through magnetic lines, or is moving parallel to the lines, no current is induced. When the loop is rotated at constant speed, it moves through the positions 1 to 5, Fig. 26. Current will be induced through the loop in the direction shown by the arrows. It cuts through the lines, at an increasing rate, until a maximum is reached as it passes at right angles through them. For each position of the loop, a certain value of current will be induced, which can be shown in the form of a curve.

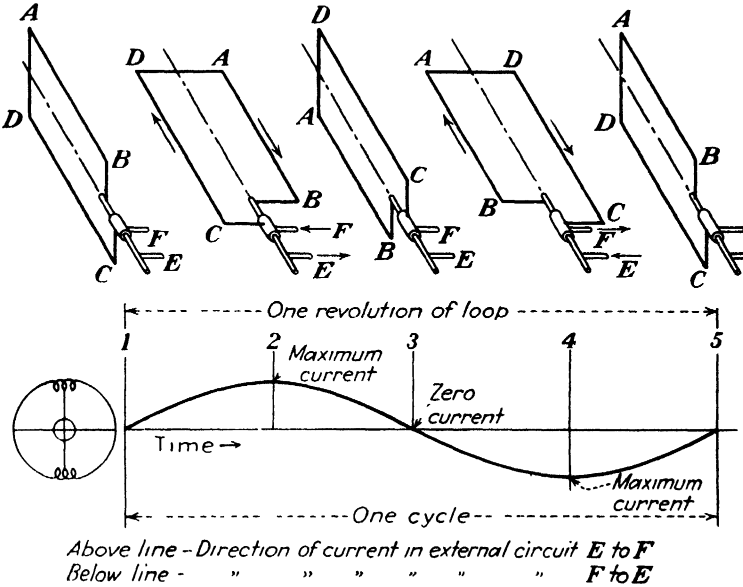

A
D
B
C
F
E
One revolution of loop
1
2
3
4
5
Maximum current
Zero current
Time→
Maximum current
One cycle
Above line - Direction of current in external circuit E to F
Below line - " " " " " " F to E

FIG. 26.—Positions of the loop in one revolution, and the resulting flow of current. This curve is called a "sine wave."

In position 1, the loop is not passing through any magnetic lines, and no current is induced. As the loop is rotated to position 2, side *AB* is moved downward and *CD* upward causing a current to flow through the loop and through the external circuit in the direction *E* to *F*. As the loop moves from position 1 to position 2, an increasing number of magnetic lines are passed through in a given time, thus increasing the magnitude of the current. From position 2 to position 3, a decreasing number of magnetic lines are passed through, and a decreasing current is induced.

In position 3, the loop is again not passing through the magnetic lines and no current is induced. At 4, the conditions of 2 are repeated, but the direction of the current to the external circuit is reversed, *F* to *E*. At 5, the loop is again in the position of 1, ready to start the cycle over.

This change of current value and also of the voltage producing it, from zero to maximum in one direction, through zero to maximum in the opposite direction, and to zero, is **one cycle.** The design arrangement of the loop and the speed at which the generator is driven determine the frequency of these cycles. Most of the supply systems in the United States operate with 60-cycle generators; that is, there are 60 of these cycles per second. Some other frequencies have been used, notably 25 and 50 cycles, but they have been largely superseded by 60 cycles as standard.

The original Edison system operated with direct current; that is, the voltage pressure and the current flow do not reverse, but continue in one direction. Instead of the external circuit being connected directly to the loop of the generator, it is so arranged that one side of the external circuit is always connected to that part of the loop in the generator which is passing through the positive direction of magnetic field. The other side of the external circuit is connected to the loop in such a way that it is supplied from the negative portion of the field. It was the development of transformers, which, as we shall see later, depend on the alternating current for their operation, that led to the replacement of direct current systems by the alternating current systems.

Current in the External Circuit.—Electricity flows with the approximate speed of light—186,000 miles per second. We must keep this figure in mind to realize that the current impulse could travel to the end of even our longest transmission lines in less than 1/600 of a second. What actually happens is that, each time the generator loop passes through the point of maximum magnetic lines, the voltage is built up in one direction and sends the current out over the external circuit and the current completes the flow through the circuit and back to another terminal of the generator. During the second one-half cycle, the voltage builds up in the opposite direction, sending current through the external loop in the reverse direction. With the 60-cycle current, one half of $\frac{1}{60}$ of a second, or $\frac{1}{120}$ of a second, of time elapses between current zeros.

In our standard *three-phase systems*, there are three loops rotating on the same shaft of the generator. The same cycle of events is true for each loop, and the curve can be drawn in the same manner for each. Three separate external circuits could be brought out of the generator, but in practice the coils are connected together in delta, or star, and three leads brought out (or four leads in the star connection with neutral). The current and voltage values hold a definite position relative to each other, as shown in Fig. 27. The current in coils *cd* reaches its maximum one-third of one cycle in time after the current in coils *ab* has reached its maximum in the same direction. The current in coils *ef* reaches its maximum one-third cycle later. This relationship follows from the relative position of the coils in the magnetic field.

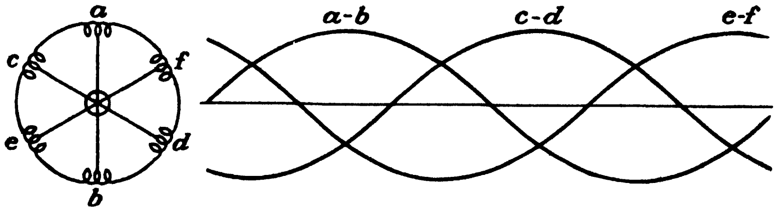


FIG. 27.—Three loops for three-phase generation.

PARALLELING AND INTERCONNECTION

With generators operating in parallel, supplying the same bus and circuits, it is necessary that the corresponding coils or loops of the generators be passing through the same corresponding point in all generators at the same time. Naturally, disaster would follow if a bus for phase 1 was being built up with the voltage from the loop in positive position of one generator and from the loop in the negative position of the other. In other words, the relative position and speeds of the two machines must be synchronized. Where all the generators are in the same power plant, this matter of synchronizing is one of mechanical and electrical control. When, however, the two generators are some distance apart, so that they are tied together by a transmission line, the problem may be somewhat more complicated.

Not only may we have more than one generating plant for one large distribution system, but also the distribution systems of neighboring cities and areas may be interconnected by transmission lines. In this case, the generating plants of the two must be synchronized, the same as are any two machines in one power plant. This subject of interconnection of power plants and of distribution systems has received considerable attention because of the economy that is often possible and because of the increase in reliability that results by having the reserve for each of the systems interconnected.

Thus, a generating plant in city *A* and another in city *B* may be interconnected. Not only is advantage taken of diversity between the load characteristics in the two cities in their daily generation and in the resulting possibilities of mutual exchange on a daily basis, but also it may be possible to pool the reserve generating capacity of the two cities. If repairs are necessary to one of the generators in city *A*, the plant of city *B* may be called upon for extra power during the repair period. In other cases, the reserve may be on a long term basis. Extra power may be supplied by city *A* to city *B* and may allow time for installation, or postponement, of a new generator in city *B*.

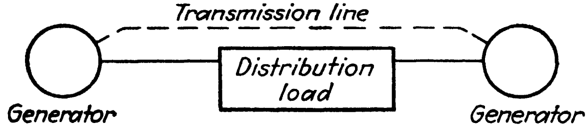


FIG. 28.—Interconnection of two generating plants.

System stability may be a problem involving distribution and transmission divisions. It is the capacity of an electric system with interconnected generating plants to remain in equilibrium under steady load conditions and to regain equilibrium after a fault disturbance has taken place. The problem is one of securing a proper balance between mechanical energy and electrical energy, and the solution is very complicated, involving governor action and inertia of the generators, line constants, speed of switching, and other characteristics.

This problem is mentioned here because it is another example of the many factors affecting the complete layout of a large electric system. It is necessary to have strong interconnecting lines to keep two systems or two parts of a single system stable. A simple example is shown in Fig. 28, with two generating plants supplying a load area between them. To maintain stability or synchronism, it may be necessary to construct the transmission line, shown dotted in the diagram, or to otherwise strengthen the interconnection.

Stability may be visualized from an analogy of two engines, one at each end of a long line shaft, with pulleys driving load between them, Fig. 29. As long as the engines pull together, they can carry the load, even if the line shaft is relatively weak. But to carry the load from one end or the other during a momentary disturbance affecting the drive of one engine or the other, it is necessary to have a stronger line shaft.

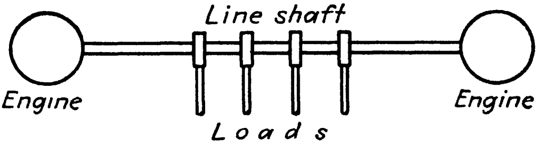


FIG. 29 Mechanical analogy of interconnection

SUMMARY

Electric voltage and current, carried by the distribution lines, derive their fundamental properties from the character of the generation. It is important in our later consideration of line design and equipment characteristics to keep in mind the curve and reversal of voltage and current values. The principle of the generator is also the principle of the motor and, in modified form, of the transformer.

To assist us in visualizing and explaining the magnetic and induction principles of lines and equipment, it is helpful to imagine a field of magnetism or lines of magnetic force. This field not only exists between the two poles of a magnet, but also surrounds a conductor that is carrying current.

Great strides have been made in the development of electrical generation and its associated mechanical and auxiliary equipment. In general, it is said that modern electric power generation stations require but 50 per cent as much fuel as was required in those built twenty-five years ago. High efficiency in converting the heat energy of fuel to mechanical energy and to electrical energy has assisted in the increasing use of electric service carried by the distribution lines.

CHAPTER V

FUNDAMENTALS OF THE ELECTRIC CIRCUIT

We explain electricity by describing its effects. Variou theories have been advanced to explain and define it, but the all come to the practical end of stating the results or actions tha accompany its flow. It is known to be a force, explained b modern physicists as caused by an invisible movement or actio of molecules.

Early experimenters held theories of fluid movement, an the decomposition of chemical compounds by electrical mean indicated a connection between chemical and electrical forces Although they chiefly directed their attention to the chemica effects, other phenomena were not overlooked. It was soo found that when passing through a conductor of any kind th electric current evolved heat, the amount of which depende on the nature of the conductor. This thermal effect is now o great practical use in electric lighting, heating, welding, etc We have noted in the previous chapter the importance of Faraday's discovery of electromagnetic induction, which has prove to be the foundation of our practical development of electrica machinery.

During this same period, several physicists and experimenter were attempting to select and define fundamental quantitie necessary for mathematical development and explanation o electric current and quantities. One of them noted the relationship between the voltage or pressure of the electric forc and the resulting current that would flow through a conducto He also showed that the current depended on the resistance o the conductor, which in turn depended on the material, th temperature, and the dimensions of the conductor, being proportional directly to its length and inversely to its area of cros section. This law is known by the experimenter's name a "Ohm's law." It is usually put in the following form: Th current is proportional to the force divided by the resistanc

It may also be stated thus: The force required to send a current through a conductor is equal to the current times the resistance.

Ohm's Law.—For practical use, Ohm's law expresses this relationship: An *ampere* is the current produced by a force of *one volt* in a circuit having a resistance of *one ohm;* that is, current in *amperes* equals force in *volts* divided by resistance in *ohms.* From this it follows that volts equals amperes times ohms and resistance equals volts divided by amperes. Stating these in arithmetic form, with I for current, E for voltage, and R for resistance,

$$I = \frac{E}{R} \qquad E = I \times R \qquad R = \frac{E}{I}$$

Power.—The unit of power is the *watt.* In the fundamental circuit, it is equal to the product of voltage and current, or volts times amperes $W = E \times I$. In our distribution system, the watts may actually be equal to, or less than, the product of volts times amperes, depending on the *power factor* of the circuit.

Work.—The unit of work is the *watt-hour.* It indicates the use of a power of *one watt* for a time of *one hour.* When the power factor is unity or 100 per cent, this may also be expressed as volt-ampere-hour, indicating the use of one volt-ampere for one hour.

These five fundamental terms are the basis for all practical electric distribution and wiring calculations. The terms are sometimes confused in common usage, and it is important that we have a clear picture of their relative meaning. Because electricity is an invisible force, the presence of which is known only by its effect on some equipment or instrument, it is often difficult to visualize these terms of measurement. It is sometimes helpful to compare them with equivalent mechanical terms.

In mechanics, the *power* means the *rate* of doing *work.* The amount of work done can be the same whether it is accomplished in one minute or one hour. But the power required to do this work is much greater, if the work is done in a short time. When we state the power of a machine, we are stating how fast it can do work. The horsepower is a unit, defined by James Watt from his experiments, that determines how many foot-pounds of work a horse could do in one minute. A horse was able to lift, by means of rope and pulley, a 150-lb. weight 220 ft. in 1 min. This rate is 150 times 220, or 33,000, ft.-lb. per minute, which is one horsepower. Electrically, 746 watts is equivalen to one mechanical horsepower.

In electrical terms, the watt is the unit of power and the watt hour is the measure of work. It is evident that a watt-hour ma be used in one hour or in one minute. If it is used in one minute the power demand is sixty times as great as it is when used i one hour.

In describing some work that we have done, we can say w carried 20 bricks, but our description is incomplete. When w say we carried 20 bricks up a ladder 10 ft. high, our description i more complete. Now, if we say we carried 20 bricks up a ladde 10 ft. high every five minutes for 8 hr., then we know how muc

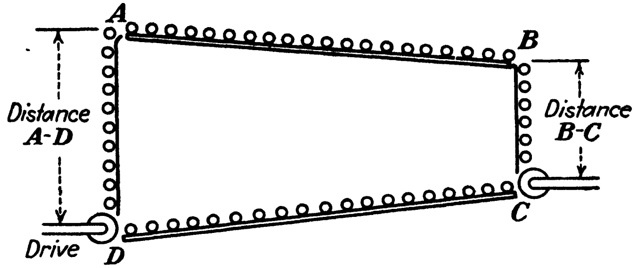


FIG. 30 —Mechanical analogy of electric circuit

work was done. We must have all these factors to have complete picture. Similarly, we may say there are 120 volt across a circuit; but if we say that in this circuit having 120 volt pressure we have 5 amperes flowing, we know more about it And when we say we have a circuit with a pressure of 120 volt and that 5 amperes flowed for 20 hr., we have described how muc work was done.

A mechanical analogy that may be of assistance is shown i Fig. 30. A board is sloped so that marbles will roll from on end to the other. Marbles placed on the board at *A* will rol to the end *B* and will fall on a paddle wheel or motor, causing it to turn and drive machinery. It is apparent that the highe point *B* is placed, the more force is transmitted to the paddle o motor by each marble as it falls.

On a lower board *CD* the marbles are returned to a point directly below *A*. They will then be carried up to *A* by a driv arrangement, which may be turned by a steam engine or a wate wheel. It is apparent that the distance *AD* between boards at the left, or sending, end must be greater than the distance at the right *BC* or receiving end.

Friction between the marbles and the board retards the movement of the marbles. This is equivalent to the resistance of an electric circuit. The number of marbles rolling down the board, or, electrically, the number of amperes flowing in a conductor, determines the flow of energy.

Mechanically, the power is proportional to the distance the marbles fall and the number of marbles falling, and electrical power is proportional to the volts times the amperes. The work done is the result of this power and the time the action continues.

Two boards are required for this mechanical arrangement for transmission of power, and two conductors are required for electrical transmission. Mechanically, there is a drop in pressure due to the difference between distances at the sending and receiving ends *AD* and *BC*. Electrically, loss of pressure or voltage drop is equivalent to this difference in distances. Loss of power is this drop in pressure times the number of marbles. Electrically, the loss of power is the voltage drop times the amperes.

Resistance in the Circuit.- All materials that conduct electricity have the inherent characteristic of resisting the flow of the current. This is a property of all electrical circuits, and it varies only with the material of the conductors and not with the arrangement of conductors. Within practical limits, it remains constant for any given material of a given size. Copper is the most widely used material for conductors, for lines and equipment, although aluminum is extensively used for transmission and rural lines and in some other construction.

Resistance is similar to friction in a mechanical arrangement. A loss of power results, which is in direct proportion to the value of the resistance. **Resistance** is expressed in **ohms.** It varies slightly with temperature, but this change is so small that it can usually be disregarded in problems concerning distribution circuits.

Resistance is a very valuable characteristic in many applications. Thus, in our heating appliances, resistance of the special wire causes the elements to reach a high temperature when current is passed through. In the incandescent lamp, resistance of the filament causes it to reach a very high temperature, almos to the burning point, when current flows through it. Heating elements employ high resistance metals.

The temperature of the conductors in our lines increases when current flows through them. Where wires are used in building construction and machinery, this temperature rise determines the maximum safe carrying capacity for the conductor. Highe currents cause deterioration and finally destruction of the insulation. Thus, it has been found by experiment and test that a No. 4 copper conductor, with rubber insulation, can safely carry 70 amperes continuously. With a cambric or tape insulation, it may carry 90 amperes safely. Actually, of course, either value may be exceeded, but beyond these values the temperature rise may become dangerous.

A standard gauge or size rating of conductors has been worked out and accepted in commercial practice. For the smaller copper conductors, the sizes are given in American Wire Gauge numbers 14, 12, 10, etc. For the larger conductors, the sizes are given in circular mils cross-sectional area.

A complete table of wire sizes, resistances, and safe current carrying capacities is given in the Appendix, and a few values are shown in Table II. The carrying capacity values are taken from the National Electrical Code. In some localities, requirements differ somewhat from these values.

TABLE II.—EXAMPLES OF RESISTANCE AND SAFE CARRYING CAPACITY

Size of wire		14	12	10	8	6	4	2
Ohms per 1,000 ft		2.52	1.59	0.999	0.649	0.407	0.257	0.161
Carrying capacity, amperes	Rubber insulation	15	20	25	35	50	70	90
	Other insulation	20	30	35	50	70	90	125

REGULATION AND EFFICIENCY

We have considered three of the fundamental measures of electric circuits—voltage, current, and resistance—and also the units of power and work. There are four additional important relationships based on these three, which are used in most practical wiring problems. They are: voltage drop, loss, regulation, and efficiency.

Most common of the distribution and wiring problems is the selection of wire size for a given load and voltage condition. Although simply finding the current and selecting the proper size wire to carry this current are often sufficient, the voltage drop or regulation and the loss or efficiency are very important considerations. For longer lines and for the larger wire sizes, as for power loads, inductive reactance and power factor must also be included. The fundamental steps are essential to the development of these further factors.

Voltage drop in a circuit is the reduction in voltage between two points, by reason of the circuit's resistance (and reactance as considered in the next chapter). It is the sending end voltage minus the receiving end voltage. For circuits involving resistance only, voltage drop is equal to the amperes times the ohms.

$$\text{Voltage drop} = I \times R = Es - Er$$

Example: A circuit with resistance of 0.161 ohm has a current of 87 amperes. What is the voltage drop?

$$\text{Voltage drop} = 0.161 \times 87 = 14 \text{ volts}$$

Voltage drop at the load is the difference between the voltage at no load and the voltage at full load. With distribution circuits, the no-load voltage at the receiving end is the same as the voltage at the sending end, since with no load there is no drop.

Example: The voltage, with no load on this circuit, is 244 volts. At full load, it is 230 volts.

$$\text{Voltage drop} = 244 - 230 = 14 \text{ volts}$$

Regulation or *percentage voltage drop* is a useful and convenient expression of the relationship between voltage drop and the voltage of the circuit.

$$\text{Regulation} = \frac{\text{Voltage drop}}{\text{Voltage}} \text{ in per cent}$$

Example: What is the regulation of the circuit in the preceding example?

$$\text{Regulation} = \frac{244 - 230}{230} = \frac{14}{230} = 0.061, \text{ or } 6.1 \text{ per cent}$$

Power loss is the difference between power input and power output, caused by the resistance. It is expressed in watts and is the loss in voltage, or voltage drop, times the current.

$$\begin{aligned}\text{Loss} &= \text{voltage drop} \times \text{current}\\ &= I \times R \times I\\ &= I \times I \times R\\ &= I^2 \times R \text{ (current value squared times total resistance)}\end{aligned}$$

Example: What is the loss in the circuit of the preceding example?

$$\text{Loss} = 87 \times 87 \times 0.161 = 1{,}218 \text{ watts}$$

Efficiency is the expression in percentage of the ratio of useful output or load to the total input. Input is equal to output plus losses.

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \text{ in per cent} = \frac{\text{Load}}{\text{Load} + \text{Losses}} = \text{in per cent}$$

$$= \frac{\text{Watts}}{\text{Watts} + I^2R} \text{ in per cent}$$

Example: The load on this circuit is 20 kw. What is the efficiency?

$$\text{Efficiency} = \frac{20{,}000}{20{,}000 + 1{,}218} = \frac{20{,}000}{21{,}218} = 0.94, \text{ or } 94 \text{ per cent}$$

PRELIMINARY CALCULATIONS FOR WIRE SIZE

Before going further with the development of the characteristics of electric circuits, it may be well to apply the fundamentals of the preceding paragraphs to several practical examples. For interior wiring, with the smaller conductors close to each other, these factors are usually sufficient for wire size selection.

Wire size determination has three features. The wire selected should be of such size that it will safely and satisfactorily convey the energy to the location where it is to be utilized. *Adequate wiring* layout requires a check of these three points:

1. The current will not heat the wire to a temperature that will injure the insulation of the wire or surrounding materials.

2. The resistance of the circuit will not cause an excessive voltage drop or loss of potential with the current to be carried.

3. The cost of the power loss in the wire will not be excessive on an economic comparison basis.

A conductor may satisfy one of these three conditions and not satisfy the two others. Hence, as a general proposition, it is always desirable to examine the conductor size selected on the basis of being large enough to have sufficient carrying capacity, to be sure that the voltage drop and power losses are satisfactory. For open wiring, or bare wire, and for most general distribution work, the voltage drop and power loss comparisons are usually of first importance, since the temperature rise will not have the hazardous possibilities that exist with interior wiring.

Finding the current is the first step in solving any circuit problem. This is found from the load on the circuit as current in amperes equals volt-amperes or watts divided by volts. For our consideration at this point, all loads may be considered as having unity power factor. Volt-amperes are thus equal to watts. It is important that we should be thoroughly familiar with these examples before going on to the theory and problems of the later sections.

Example: A load of 20 kw. at a voltage of 230 is 500 ft. from the service. What is the minimum size of rubber insulated wire? What are the voltage drop and the power loss? Find the regulation and efficiency.

Solution: Current $= \frac{20,000}{230} = 87$ amperes

From the table: No. 2 rubber insulated wire.
Total resistance: 2 wires × 500 ft. = 1,000 ft. $R = 0.161$ ohm
Voltage drop: $I \times R = 87 \times 0.161 = 14$ volts
Loss: $I^2 \times R = 87 \times 87 \times 0.161 = 1,218$ watts, or.

$$\text{Current} \times \text{Volts drop} = 87 \times 14 = 1,218 \text{ watts}$$

Sending voltage: $230 + 14 = 244$ volts

Regulation: $\frac{14}{230} = 0.061 = 6.1$ per cent

Efficiency: $\frac{20,000}{20,000 + 1,218} = 0.94 = 94$ per cent

Example: A load of 15 kva. at 240 volts is 300 ft. from the service. (1) What is the minimum size of braid insulated wire that can be used? What is the regulation with this wire? (2) If the regulation is to be limited to 3 per cent what size of wire should be used?

(1) *Solution:* Current $= \frac{15{,}000}{240} = 62.5$ amperes

From the table: No. 6 braid insulated wire can be used.

Total resistance: 2 wires × 300 = 600 ft.;

$$\frac{600}{1{,}000} \times 0.407 = 0.244 \text{ ohm}$$

Voltage drop: 62.5 × 0.244 = 15.2 volts

Regulation: $\frac{15.2}{240} = 0.063$ or 6.3 per cent with No. 6 wire

(2) *To limit regulation to 3 per cent:*

Allowable voltage drop = 3 per cent of 240 = 7.2 volts

Since voltage drop $= I \times R$

$$7.2 = 62.5 \times R$$

Allowable resistance $R = \frac{7.2}{62.5} = 0.115$ ohm

This resistance is in 2 × 300 ft. = 600 ft. of wire

Allowable resistance per 1,000 ft.; $\frac{1{,}000}{600} \times 0.115 = 0.192$ ohm

No. 2 wire, with 0 161 ohm per 1,000 ft., is nearest size with less than this allowable resistance

To check actual regulation:

600 ft. has $\frac{600}{1{,}000} \times 0.161 = 0.097$ ohm

Drop = 62.5 × 0.097 = 6 volts

Regulation is: $\frac{6}{240} = 0.025$ or 2.5 per cent with No. 2 wire

This example illustrates the practical point that a wire which will safely carry a given current may not be large enough to give satisfactory voltage service. Whether 6 per cent regulation is too high or not will depend on the load conditions. The third point is a check of power loss cost, as in one of the following problems.

SUMMARY AND PROBLEMS

Electricity itself has no accepted definition, and we explain it by describing its effects. It is a force—silent and invisible—

a force of destruction if not properly controlled, yet a powerful, practical, and universal force when intelligently used and controlled.

There are three fundamental units for measurement in electric circuits: (1) volt, unit of pressure or force; (2) ampere, unit of flow of current; and (3) ohm, unit of resistance to the flow. Ohm's law expresses the relationship between these three units: An *ampere* is the current produced by a force of one *volt* in a circuit having a resistance of one *ohm.* For our practical use this is expressed

$$\text{Current in amperes} = \frac{\text{Force in volts}}{\text{Resistance in ohms}}$$

$$I = \frac{E}{R}, \qquad \text{and also,} \qquad E = I \times R$$

A fundamental problem in all electrical circuit layout is to determine the size of the conductor required. The first step is to *find the current* to be carried for the load. The conductor selected should satisfy three conditions: (1) The current will not heat it to a dangerous temperature. (2) The voltage drop will not be excessive. (3) The cost of the power loss will not be excessive, on an economic comparison basis.

For direct current calculations, for simple wiring calculations, and for preliminary calculations of all circuits resistance only may be used in finding the voltage drop. For alternating current circuits, particularly for power loads, for open wiring, heavy conductors, or long circuits, inductive reactance of the circuit and power factor of the load must also be considered.

Problems:

1. What are the current and minimum size of rubber covered wire for each of the following one-phase loads?

a. 50 kva. at 240 volts.
b. 370 watts at 120 volts.
c. 6,000 watts at 120 volts.

2. What is the voltage drop in a circuit of 800 ft. to a 15-kva. 440-volt load, if No. 6 wire is used?

3. What are the loss and efficiency in the line of (2)?

4. What wire size should be used for a load of 5 kva. at 120 volts, if the regulation is limited to 3 per cent and the distance is 200 ft.?

5. A load of 10 kva. at 240 volts is 500 ft. from the meter. No. 6 wire will carry this load, but No. 4 will have less line loss. You are asked to decide which wire to use. Base your answer on the saving over a period of two years, if the load is used 40 hr. per week and energy costs 3 cents per kilowatt-hour. Take difference in cost of wire per foot at 1.5 cents.

NOTE: Compare difference in wire cost and saving in energy cost.

6. What is the minimum size of rubber insulated wire for a 50-kva. one-phase 240-volt load? Find the voltage drop and loss in this line if the load is 400 ft. from the service. What size of wire should be used to limit the voltage drop to one-half the value found for the minimum size of wire?

7. For the conditions of Prob. 6 and the load time and energy cost of Prob. 5, is there a saving with the larger wire, if it costs 25 cents per foot more?

NOTE: Answers to these and succeeding problems will be found in the Appendix, to enable the reader to check his own calculations.

CHAPTER VI

INDUCTANCE AND RELATED CHARACTERISTICS

In our discussion of generation, we noted that, when a conductor is moved through a magnetic field, a current is caused to flow in the conductor. The converse of this is also true—when a current flows through a conductor, a magnetic field is set up around the conductor. This field may be imagined or visualized as a series of lines of force. It is of fundamental importance in the operation of alternating current circuits and equipment.

Inductance is a property of electric circuits that is caused by this magnetic field surrounding the conductor. When the current in the conductor changes, this magnetic field changes in the same proportion. While current is increasing, energy is stored in the magnetic field; while the current is decreasing, the magnetic stored energy is returned to the electric circuit. Also, the magnetic stored energy may be transferred to an adjacent electric circuit, which is the fundamental of transformer action.

Inductance has an electrical effect similar to mechanical inertia. Any moving mass will resist a change in velocity. A flywheel, for instance, tends to continue turning when its source of power is removed, and also its inertia opposes any effort to speed up the movement. Thus the motion of the flywheel, or other moving mass, lags behind the force that produces the motion. The flow of current in an electric circuit in which there is inductance also lags behind the voltage force that produces it.

In a direct current circuit, the effect of inductance is present only during starting and stopping, or during changes, of the current flow, as in the case of the flywheel. In an alternating current circuit, however, the current is continually starting and stopping. Every one-half cycle the current starts at zero value, builds up to maximum in one direction and then decreases to zero. During the next one-half cycle, it builds up in the opposite direction. The inductive effect is, therefore, dependent on the frequency of the current, increasing with increased number of cycles per second.

In Fig. 31, one conductor of a circuit is shown in (*a*) with lines representing the magnetic field. The magnetic lines have direction corresponding to the direction of current flow. In (*b*), the ends of two conductors are shown, with the circles representing the magnetic field. Current is flowing in a direction away from the reader in the conductor on the left and toward the reader in the conductor on the right. Arrows represent the corresponding direction of the magnetic lines. In (*c*), the conductors are closer together and the magnetic fields of the two tend to neutralize each other. This effect is of fundamental importance in our later consideration of inductive reactance.

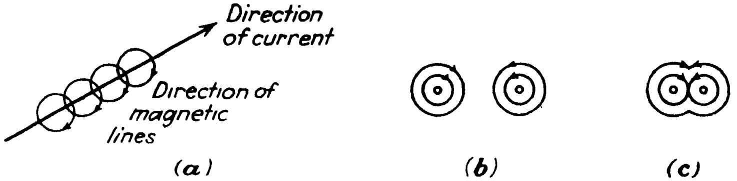


FIG. 31.—Magnetic field around a conductor with current flow

Importance of Inductance.—Alternating current was adopted principally to take advantage of the inductive characteristic in the operation of transformers. This characteristic has also helped to simplify the design of motors, by eliminating the brushes and commutator necessary with direct current. At the same time, however, other problems were introduced by the presence of inductance. Inductive reactance in the circuit and reactive power required by motor loads, as measured by power factor, are two important considerations with alternating current supply.

We have seen that the development and growth of electric supply, and of electric distribution in particular, have centered in the development and application of transformers. The fundamental layout and economics of our whole system are built upon the basis of being able to transmit and distribute at higher voltages than can be used for general utilization. Many economies have also been possible in wiring and application, because of the use of alternating current. To get a broad picture of the importance of inductance, it may be well to sketch briefly the points where it affects our circuits most.

In Fig. 32 are shown the five elements of a complete electric supply and utilization circuit: generator, distribution line, transformer, service line, and motor.

In the generator, conductors are forced by mechanical drive to cut through magnetic lines. This sets up a current in the conductors, and this current is carried by the distribution line to the transformer.

In the transformer, current flowing through the conductors of the primary winding builds up a magnetic field. The magnetic stored energy is held by an iron core, around which is also a secondary winding. When the current dies down to zero in the primary, the magnetic lines collapse, cutting through the interlinked secondary winding This causes a current to flow in the secondary, according to the same principle as in the generator. No physical motion takes place in the transformer, the movement of the magnetic field serving this purpose.

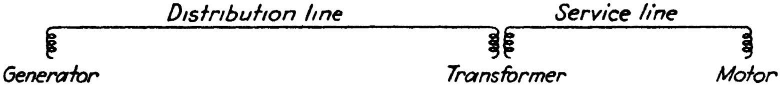


FIG. 32.—Elements of an electric supply circuit to a motor

The only alternative to the transformer would be a motor generator, with the motor driving the generator and starting a new current to flow out over the service line.

In the motor, the current in a winding builds up a magnetic pull in one direction, drawing a pole of the motor toward it. During the next one-half cycle of the alternating current flow, this same winding has current in the opposite direction. This causes the magnetic action to reverse also and a repulsion to take the place of the pull. By proper arrangement of the windings and poles, motion is set up by the rotation of the magnetic field from one winding to another.

In the direct current motor, this rotation of magnetic action is obtained with a commutator and brush arrangement, which serves to move the current action from one winding to the next. Elimination of the commutator and brushes has helped in greatly simplifying the motor.

Around the conductors of the distribution and service lines, a similar magnetic field action takes place. Here it does no good but, like the resistance of the conductors, must be taken into account in the design of the circuit. The inductive effect is to retard in time the flow of current through the conductors. This effect is also present in the transformer and motor.

In distribution design, both of the primary lines and of service and wiring lines, we are concerned with two results of this inductive effect.

1. Because of inductance inherent principally in motors, and to some extent in other loads, the current is retarded in time relative to the voltage, more current being thus required to produce a certain amount of power. This is expressed as *power factor.*

2. Because of inductance in the supply circuits, the current is further retarded in its flow. This effect is expressed in *inductive reactance* and for given conditions is measured in ohms, similar to the values for resistance of the conductors.

POWER FACTOR

Power factor was defined in the section on load characteristics (Chap. II). It is a ratio or percentage figure to express the relationship between the watts of a load and the product of volts and amperes necessary to supply the load.

Watts, which is the measure of actual power, is the product of volts and ampere values *at the same time.* **Volt-amperes,** which is the measure of volts and current on the line, is the product of these units, regardless of their *time displacement.* They are also referred to as "true" power (watts) and "apparent" power (volt-amperes).

$$\text{Power factor} = \frac{\text{True power}}{\text{Apparent power}} = \frac{\text{Watts}}{\text{Volt-amperes}}$$

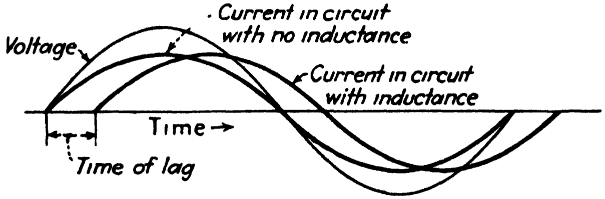
or

$$\text{P.F.} = \frac{W}{E \times I} \qquad \text{and} \qquad W = E \times I \times \text{P.F.}$$

therefore;

$$\mathbf{I} = \frac{\mathbf{W}}{\mathbf{E \times P.F.}} \textit{ for 1-phase circuits}$$

Figure 33 shows the time characteristics of current in a circuit with unity and with low power factors. The voltage and current curves starting together, reaching maximum at the same time, and passing through zero together are in a circuit with unity power factor. Their effective or actual product in watts is the same as the product of the volts and the amperes measured separately.



Current in circuit with no inductance
Voltage
Current in circuit with inductance
Time →
Time of lag

FIG. 33.—Current reaches maximum with voltage in a circuit with no inductance, but there is a time lag with inductance in circuit.

When, however, the current does not follow exactly with the voltage, that is, when it lags in time, the effectiveness or power is reduced. Their product, at any instant, is less than when they are together in time Therefore, to produce a given power one or the other must be larger. Actual power is best found by a wattmeter, which automatically accounts for the effect of time difference.

A *unity* power factor means that there is no time lag and that watts equals volt-amperes. A 50 per cent power factor means that the watts are only one-half the volt-ampere product. Also, it means that twice as much current is required to produce a given amount of power, compared with the case of unity or 100 per cent power factor.

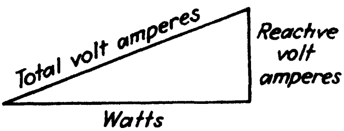


FIG 34 —Addition of actual load and reactive component of total volt-amperes.

When the power factor is less than unity, the additional current is necessary for the *reactive* part of the load. The true power in watts and this reactive load in volt-amperes are added at right angles to give total volt-amperes of the circuit. This is shown in Fig. 34. Watts are measured to some scale along a horizontal line, and reactive volt-amperes are measured to the same scale along a vertical line, beginning at one end of the horizontal line. The diagonal or hypotenuse line can then be measured to scale to give the value of total volt-amperes.

Analogies are useful in explaining power factor. In Fig. 35 is sketched a railroad car being pushed by a locomotive. If the locomotive can get on the same track with the car and push from directly behind, all the force comes out as useful work to push the car along the track. However, if the locomotive cannot get on the same track but has to be on a parallel track and push the car from an angle, as shown in the figure, the amount of force may be the same, but the amount of actual push on the car is not the same, because there is a tendency to push the car sideways off the track. It will take more force to push the car from this angle. The power output from the locomotive is then made up of two parts, the actual work and the lost force. This is equivalent in the electrical circuit to the actual power and to that which is used to overcome inductive reactance.

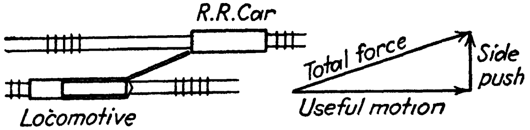


FIG. 35.—An analogy to explain power factor.

Another analogy is shown in Fig. 36, in which a boat is represented crossing a stream in which there is a rapid flow. To arrive at a point directly across stream, it must actually be rowed toward a point upstream. The stream flow puts the applied force in the boat "out of phase" with the motion of the boat. Although the useful power or accomplishment is to row from point *A* to *B*, the power required is to row from point *A* to *C*. The part of the power required to row upstream, an amount equivalent to *B* to *C*, is to overcome the stream flow.

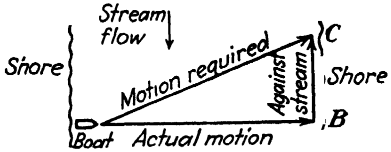


FIG. 36.—Stream flow analogy of reactive load.

Power load, motors for industrial and appliance drive, contribute most to the reduction of power factor, because they require large amounts of reactive power in their operation. Other appliances may also require reactive power, notably transformers for certain types of signs, for welding equipment, etc.

Metering of energy sold by the electric supply utility is generally in watts and watt-hours. Additional equipment is necessary to register volt-amperes and adds considerably to the complications and expense of metering. For the usual lighting and small appliance load of domestic service, the power factor is ordinarily high, and watt-hour metering is sufficient for an actual measure of the load. Contracts for industrial load supply may contain clauses providing for metering on a kilovolt-ampere or power factor basis.

Improvement of power factor is often justified. It necessitates additional equipment, either at the loads or connected to the supply lines. Whether this added investment is justified or not depends almost entirely on economic comparisons. The cost must be compared with that for adding more line and transformer capacity. In other cases, an improvement in voltage regulation may be desired, and a reduction of current by power factor improvement should be compared with other means of regulating voltage or reducing the voltage drop.

Since heating of transformers determines the size required and voltage drop and loss determine wire size required, the increased current with low power factor increases the investment required. Or, stated another way, the power *in watts* that may be carried over a given line and transformer supply system is less when the excitation or inductive current is high.

In general, there is no way to eliminate this component of current, but we can counteract, or neutralize, it by adding another load to the circuit in the form of condenser or capacitor equipment. This load draws a component of current over the line that *goes ahead* of the voltage, and, when it is added to the component that is *lagging behind*, the total will be more nearly in phase with the voltage.

Possible corrective equipment includes:

At the load—(1) synchronous motors with high power factor, or leading power factor, on some of the larger drives; (2) static condensers, or capacitors.

On the distribution system—(1) synchronous condensers or capacitors in the substations; (2) capacitors on the lines.

Development of lower cost capacitor equipment in recent years has led to more interest in this subject than formerly. Increasing power loads have also tended to lower power factors somewhat. Addition of refrigerators, blowers, and other motor operated appliances has caused the residential load power factor to be lowered, although predominance of lighting load still keeps it relatively high. So far, economics point to power factor correction for many industrial loads, or on feeders supplying them, but not in general on the residential load feeders.

Another method of improving power factor is the use of motors with separate excitation for the field windings. It is possible to control the reactive power of these motors to give high power factor, or even leading enough to offset low or lagging power factor in other motors. An important application of this principle is the synchronous motor without load, or synchronous condenser, often used in the distribution substations to improve the power factor on the transmission lines supplying a large load area.

In many cases, the wiring and load conditions justify power factor correction at the load. Some electric company rates have offered inducement for such correction. As correction on the distribution lines can usually be accomplished at less cost, the answer again depends on economic comparisons.

Calculations for power factor improvement are considered in the next chapter. The following examples, and several problems at the end of this chapter, show the importance of including power factor in practical calculations.

Example: A load of 50 kw. is supplied at 240 volts, single-phase. What is the current with power factor of (*a*) 100 per cent, (*b*) 80 per cent, (*c*) 65 per cent, (*d*) 50 per cent?

Solution: Current, $I = \dfrac{\text{Watts}}{E \times \text{P.F.}}$

(*a*) $I = \dfrac{50{,}000}{240 \times 1.00} = 208$ amperes

(*b*) $I = \dfrac{50{,}000}{240 \times 0.80} = 260$ amperes

(*c*) $I = \dfrac{50{,}000}{240 \times 0.65} = 320$ amperes

(*d*) $I = \dfrac{50{,}000}{240 \times 0.50} = 416$ amperes

Example: An 80-kw. load supplied at 480 volts, single-phase, draws 255 amperes. Capacitors are added, and the current is reduced to 200 amperes. What are the original and the improved power factors?

Solution: Power factor $= \dfrac{\text{Watts}}{\text{Volt-amperes}}$

$$\text{Original P.F.} = \frac{80{,}000}{480 \times 255} = 0.65 = 65 \text{ per cent}$$

$$\text{Improved P.F.} = \frac{80{,}000}{480 \times 200} = 0.83 = 83 \text{ per cent}$$

INDUCTIVE REACTANCE

Inductive reactance is the practical quantity that depends on the value of inductance and on the frequency of the alternating current. Inductance of the line depends on the spacing or distance between conductors or wires of the line and to a less extent on the size of the conductors. The greater the distance between conductors of a circuit, the greater is the inductance and the inductive reactance.

For small wires, close together, the inductive reactance may be neglected. As the size of the wires increases, or as the spacing between them increases, the relative importance of inductive reactance increases also. Thus, for interior wiring in conduit or cable assemblies, with No. 14 wire, resistance only may be used. For No. 0000 wire, however, the inductive reactance is as great as the resistance, even with close spacing. With 15 in. separation, the inductive reactance is twice as great as the resistance.

Referring again to Fig. 31 and comparing (*b*) and (*c*), we can see why the distance between conductors is important in considering the reactance. When the wires are close together, their magnetic fields, being in opposite directions, tend to neutralize each other. As they are moved apart, the neutralizing effect is lost, and the reactance increases.

The quantity of inductive reactance also varies with the frequency of the alternating current. This is apparent; for the more times the magnetic field collapses, the greater will be the inertia effect of the current. Inductive reactance has been calculated and checked by tests, and values are given in reference tables for all conditions of spacing and conductor size. Table III gives a few values, and a complete table will be found in the Appendix. These values are for 60-cycle current and are in ohms per 1,000 ft. for each wire of the circuit. Note the increase in reactance for the increase in spacing. Resistance values are also shown for comparison.

TABLE III.—EXAMPLES OF INDUCTIVE REACTANCE VALUES

Spacing, in.	Inductive reactance X per wire, ohms per 1,000 ft			
	Size of wire			
	8	4	2	0000
	$R = 0.649$	$R = 0.257$	$R = 0.161$	$R = 0.050$
2	0.085	0.074	0.069	0.056
10	0.121	0.111	0.105	0.093
15	0.131	0.120	0.115	0.102
36	0.151	0.140	0.135	0.122

Impedance.—The *vector* sum of resistance and inductive reactance is called impedance (Fig. 37). They are added at right angles, as was indicated for watts and reactive power. Resistance is usually denoted by the abbreviation R, inductive reactance by X, and impedance by Z. With alternating current problems, we use Ohm's law as with direct current and substitute Z, or sometimes X only, in place of R in the formula $E = I \times R$ and its other forms.

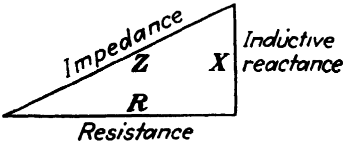


FIG. 37.—Resistance and inductive reactance are added together at right angles, to give impedance.

Example: What are the resistance and inductive reactance of a two-wire line 1,000 ft. long, (*a*) spaced 10 in., with No. 4 wire? (*b*) No. 2 wire spaced 36 in.? (*c*) No. 00 wire spaced 24 in.?

Solution:

(*a*) No. 4 $R = 2 \times 0.257 = 0.514$ ohm
10 in. $X = 2 \times 0.111 = 0.222$ ohm
(*b*) No. 2 $R = 2 \times 0.161 = 0.322$ ohm
36 in. $X = 2 \times 0.135 = 0.270$ ohm
(*c*) No. 00 $R = 2 \times 0.080 = 0.160$ ohm
24 in. $X = 2 \times 0.118 = 0.236$ ohm

NOTE: Reference to Appendix table for No. 00.

CAPACITANCE

Capacitance is the property of an electric circuit that causes it to hold a charge of electricity. It is particularly important in the case of an electric condenser, which may be most familiar to many of us as used in radio circuits. In a condenser, two or more conductors or plates are separated by a dielectric or insulator. When voltage is applied across the conductor plates, a certain quantity of electricity must be passed into it before it acquires a voltage potential.

A condenser might be considered as similar to a vacuum. When air pressure is applied to a vacuum tank, the tank must first be filled before it acquires a pressure. When voltage pressure is applied to a condenser, the current is drawn ahead before the voltage is built up on the plates. During each half-cycle of the alternating current flow, the condenser is charged and then gives back its charge to the supply circuit.

Capacitance has an effect directly opposite that of inductance. Where inductance causes the current to lag behind the voltage, capacitance causes current to go ahead of the voltage.

Since all line conductors are insulated from each other, they have some capacitance present. But for distribution and ordinary transmission lines, the amount is so small that it is negligible. For long transmission lines, and especially for long cable lines, this effect is an important characteristic.

When inductive reactance is quite large on a line, or when the line is supplying a load with low power factor, it may be desirable to cancel part of the inductive effect by adding capacitance in the form of condensers, or capacitors. The amount required for a desired result or amount of correction is considered in the next chapter.

SUMMARY AND PROBLEMS

In Chap. V, we considered the fundamentals of the simple electric circuit, in which resistance only limits the flow of current and in which the current is fully effective in the load. In this chapter, we have added the fundamentals that must be considered when inductance is present in the load and supply circuits. We noted that inductance is essential in our alternating current system and that we cannot eliminate its effect. We can, however, add corrective equipment or improvement measures to reduce or offset the effects.

Resistance may be thought of as being equivalent to friction in a machine. In a similar way, inductance is analogous to the inertia of a machine. It causes the movement or flow to lag behind the force. Capacitance has an opposite effect on the current, causing it to go ahead of, or lead, the voltage.

We want to be sure to get the point of the power factor examples—that, for the same power load, the current may actually be half again as much, or even twice as much, as we would expect from a wattmeter measurement only—and the point of the inductive reactance examples—that the voltage drop in a line may be much larger, even several times, what we would calculate from resistance of the wire only.

Problems:

1. With a current of 120 amperes, what is the minimum size wire with weatherproof insulation that should be used? What is the resistance per 1,000 ft., and what is the inductive reactance if the wires are spaced 10 in. apart?

2. What is the minimum size of rubber insulated wire to be used for each condition of Example on page 74? What are the resistance and the inductive reactance of a line 400 ft. long, with spacing of 2 in., 10 in., with these wire sizes?

3. A load of 500 kw. is supplied by a one-phase 2,400-volt line. The current is the maximum that can be carried by the supply equipment. Power factor is 60 per cent. What must the improved power factor be to allow adding 150 kw. without exceeding the present current?

4. A load of 55 kw. is supplied at 240 volts, one-phase. What is the current at 60 per cent P.F., and what is it after the power factor is raised to 80 per cent?

5. What are the total R and X values for these two-wire lines:

(*a*) No. 6 wire, 1,000 ft., spaced 36 in.?
(*b*) No. 2 wire, 4,000 ft., spaced 24 in.?
(*c*) No. 00 wire, 4 miles, spaced 42 in.?

6. Which of these statements are correct, and which are not?

(*a*) With No. 14 wire in conduit, reactance is negligible compared with the resistance.

(*b*) With No. 4 wire spaced 4 ft., reactance should not be neglected in calculating voltage drop.

(*c*) With 1,000,000 c.m. wire spaced 15 in., reactance is eight times as much as resistance.

(*d*) When the power factor is above 90 per cent, its exact value is of little importance in practical calculations.

CHAPTER VII

TOOLS FOR ELECTRICAL PROBLEMS

Mathematics and diagrams are useful tools for the solution of mechanical and electrical problems. By experience and experiment, certain results have been found to follow certain actions. The relation of force and movements, pressure and bending, etc., have, for convenience, been expressed in terms that can be used in new combinations as desired. All the original development of electrical equipment was by cut and try methods. Generators, motors, and transformers were built and tried, and, if they operated, their capacity was determined by the load they would carry without getting so hot that they were destroyed. The next units built were then made the same, or with certain parts larger or smaller to improve on the original. Definite relationships were gradually developed, so that designs could be worked out before the shop work was started.

We have noted that early experimenters defined electrical characteristics by their chemical reactions and effects. Faraday and later experimenters described the magnetic field by imagining lines of force between the poles of the magnet or surrounding the electrical conductor. Ohm expressed the relation between electrical pressure and the current that would flow through a conductor, in a mathematical formula. Other experimenters composed units for fundamentals and observed forces and results. It was not until after equipment was being built for commercial use, following Edison's pioneer plant, that mathematics was extensively applied to the designs.

Charles P. Steinmetz was at work in a machine tool factory, where transformers were being built as a side line, when he worked out the relationship that led to the law of hysteresis, which is the foundation for transformer and electrical machinery design. Benjamin G. Lamme was a helper in the test room where some of the first generators and motors were run after their construction. Accounts of this early period tell of the workmen getting behind convenient posts and at safe distances when the switches were closed to start the tests on a new machine. By studying test results, Lamme was able to see certain relationships that could be expressed mathematically.

These two men had been well educated in mathematics and mechanics. Following their practical experience, they became leaders in the development of electrical equipment by calculation and design. Trial and error methods have been largely superseded by formulas and tables of calculated and test values. It is interesting to note that experience, observation, and tests are the starting points for these methods of calculation.

Although the design of machinery, long transmission lines, and complicated networks require the use of trigonometry, calculus, differential equations, etc., they are not necessary for the solution of the usual distribution problems. An understanding of fundamental principles and equipment theory, together with a few arithmetic operations, is sufficient for the everyday problems met with. A clear picture of the factors involved in a given practical situation is the first essential toward the solution. A diagram of the parts and units should be the first step.

Graphical methods, with the assistance of a chart, are described and used for our present purpose. The more exact mathematical methods are recommended for further and more advanced study. A review of several arithmetic fundamentals may be in order for some readers and is, therefore, included in the Appendix. Of particular importance is the transposition of figures and proportion. It may be surprising to many, that the incorrect placing of decimal points is one of the most common sources of error, not only in field solutions of problems, but in engineering office solutions as well. An answer of 274. amperes instead of 27.4 amperes defeats an otherwise good job.

VECTORS

Many of the steps in solving electrical problems are greatly simplified by diagrams based on the time differences between voltage and current waves. These are called vector diagrams. Likewise, many quantities can be not only visualized but also determined by the use of such diagrams. The addition of resistance and inductive reactance to give impedance and of watts and reactive-volt-amperes to give volt-amperes, referred to in the preceding chapter, are two examples. Tensions in guy wires and other mechanical problems can be solved with a similar method.

Vectors, used for electrical quantities, are straight lines drawn to scale in length and to represent relative *time* in their position and direction. In mechanical design, vectors represent magnitude in their length and relative *direction* of the force acting on a body. Thus, if the scale is 1 in. equals 100 lb., a line 2½ in. long represents 250 lb. Electrically, if 1 in. equals 100 volts, a line 2½ in. long represents 250 volts (Fig. 38).

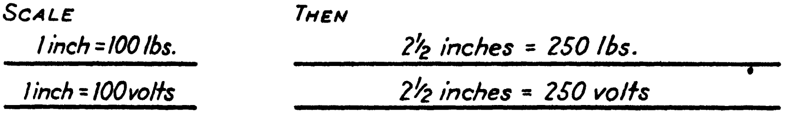


FIG. 38.—Lines drawn to scale length to show magnitude.

To illustrate the time characteristics of electrical vectors, we can slow down the 60-cycle per second frequency to 1 cycle per hour (Fig. 39). With one cycle in one hour instead of one-sixtieth of a second, the minute hand of a clock will make one revolution while the voltage and current waves are going through a cycle. Then, if we say that the cycle starts with the minute hand pointing to 12 on the clock and the voltage wave at zero, the hand will point to 3, or 15 minutes, when the voltage wave is maximum in one direction.

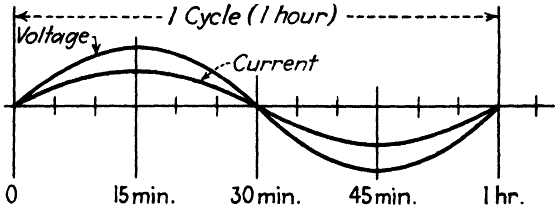


FIG. 39.—Current and voltage curves on a one-hour scale, to explain vectors. Circuit with no inductance.

The hand will point down, to 30 minutes, when the voltage is again zero. It will point to the left, or 45 minutes, when the voltage wave is maximum in the opposite direction and will be again pointing up to 12 when the voltage is again zero. For our purposes, we can say that the direction toward 3, representing the maximum of the voltage in one direction, is the vector representing this particular voltage wave. If the current reaches a maximum at the same time, its vector will coincide in direction with this vector.

If, however, the current lags in time behind the voltage, owing to inductive reactance in the circuit, the current maximum will occur after the voltage. For the amount of lag shown in Fig. 40, the current vector would be at 20 minutes. The voltage and current vectors would then be as shown in Fig. 41*a*. Similarly, we could let the current vector be represented by the direction toward 15 minutes, and the voltage would then be in direction toward 2, or 10 minutes, as shown in Fig. 41*b*.

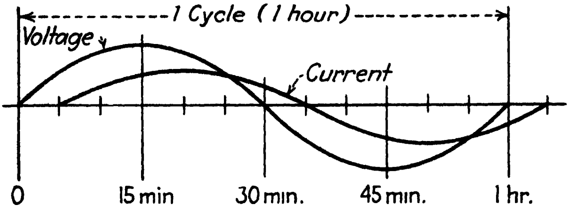
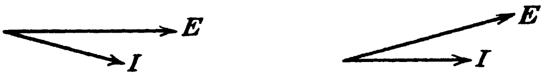


FIG. 40.—Time lag on a one-hour scale, in circuit with inductive reactance.



(*a*) (*b*)

FIG. 41.—Voltage, *E*, and current, *I*, vectors for the lag shown in Fig. 40.

Applying this idea to the three-phase voltage waves shown in Chap. IV, we can draw a vector diagram for the three voltages, as shown in Fig. 42. Phase *A* is represented by a vector toward 3, or 15 minutes. Voltage of phase *B* reaches maximum 20 minutes later, or when the hand points to 7, and that of phase *C*, another 20 minutes later, or with hand pointing to 11. The three vectors are shown in Fig. 43*a*, with their origin at a common point.

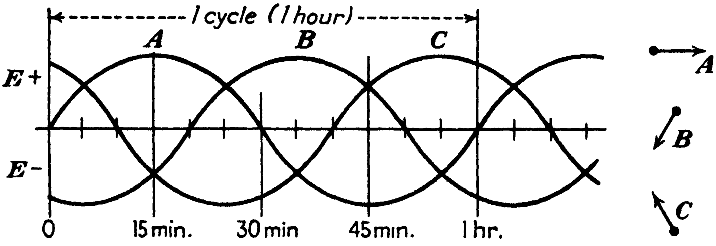


FIG. 42.—Voltage curves for three-phase, on a one-hour scale to explain vectors

We could show the vector for A at 12, B at 20 minutes, or 4 on the clock, and C at 20 minutes later, or 8, giving the diagram of Fig. 43*b*. Or we can show it as in *c*, with one vector pointing to 6 and the others to 10 and 2. Any of these diagrams can be assumed as the basis for an analysis, but we must keep the same relative directions throughout this analysis. It is important to remember that we are dealing with *relative time*, and, if voltage wave A is represented by a horizontal direction vector, it cannot be moved unless we also move all related vectors.

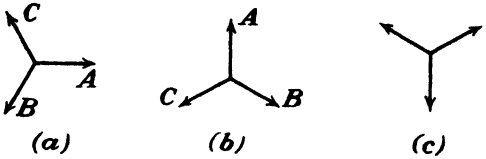


FIG. 43 The three vectors are then drawn with a common origin. In (*a*) the positions of Fig. 42 are used In (*b*) and (*c*), other alternative positions are used

THREE-PHASE—SQUARE ROOT OF 3

Practically all generation and distribution are with a three-phase system. This makes the most effective use of conductors and effects many savings in distribution and also in power applications. In all problems of three-phase circuits, the square root of three—$\sqrt{3}$—is used.

We can illustrate this value by accurately drawing the vector diagram of the three voltages. The three lines will be of equal length, and the angles between them will be equal. With the length of the lines 1 in., Fig. 44, the distance between their points or outer ends will be about $1\frac{3}{4}$ in. By more accurate solution, graphically or mathematically, this value is found to be 1.732, which is $\sqrt{3}$ (1.73 is ordinarily used).

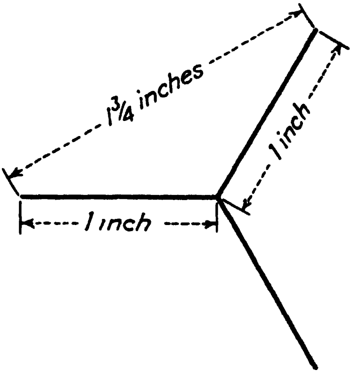


FIG. 44.—Graphical representation of the value $\sqrt{3}$ or 1.73. The phase to phase voltage is 1.73 times the phase to neutral voltage.

This value expresses the relationship between the phase to neutral and the phase to phase voltages. Thus, in a three-phase four-wire distribution line, the voltage from neutral to each phase wire is 2,400, and the voltage between any two of the other three wires is 1.732 times 2,400, or 4,157 volts. In three-phase three-wire lines, the neutral point is not carried by a wire, or it may be imaginary. The phase to neutral voltage is the phase to phase voltage divided by 1.73. Thus, for a 13,200-volt line, the phase to neutral voltage is 13,200 divided by 1.73, equals 7,630 volts.

Now, if we consider that each phase wire is carrying one-third of the total power of the circuit, each wire with the neutral may be considered as a single circuit to determine the current. To find the current in a 4,157-volt three-phase circuit, with a load of 75 kva., we can first find the load per phase as 75 divided by 3, equals 25 kva. The voltage phase to neutral is 4,157 volts divided by 1.73, equals 2,400 volts. The current of each conductor is then 25,000 divided by 2,400, equals 10.4 amperes. The general formula is derived as

$$\text{Load carried in each wire} = \frac{\text{Total load}}{3} \text{ or } \frac{VA}{3}$$

$$\text{Voltage of each wire to neutral} = \frac{\text{Voltage}}{\sqrt{3}} \text{ or } \frac{E}{\sqrt{3}}$$

where E is the phase to phase voltage

$$\text{Current in each wire, } I = \frac{VA}{3} \div \frac{E}{\sqrt{3}}$$

and

$$I = \frac{VA}{3} \times \frac{\sqrt{3}}{E} = \frac{VA}{\sqrt{3} \times \sqrt{3}} \times \frac{\sqrt{3}}{E}$$
$$= \frac{VA}{\sqrt{3} \times E}$$

Since Watts,

$$W = \text{Volt-amperes} \times \text{Power factor} = VA \times \text{P.F.}$$
$$VA = \frac{W}{\text{P.F.}}$$

Substituting,

$$I = \frac{VA}{\sqrt{3} \times E} = \frac{W}{\text{P.F.}} \times \frac{1}{\sqrt{3} \times E}$$

and

$$I = \frac{W}{\sqrt{3} \times E \times P.F.} \text{ for 3-phase circuits}$$

Example: What are the current and minimum size of rubber insulated wire for 50 kva. (*a*) single-phase 240 volts, (*b*) three-phase 240 volts, and (*c*) what is the saving in copper weight required for a line 400 ft. long?

$$(a)\ \text{Single-phase } I = \frac{50{,}000}{240 \times 1.00} = 208.\ \text{amperes}$$

Use No. 0000 wire

$$(b)\ \text{Three-phase } I = \frac{50{,}000}{\sqrt{3} \times 240 \times 1.00} = 120.\ \text{amperes}$$

Use No. 0 wire

(*c*) No. 0000 copper weighs 641 lb. per 1,000 ft., and No. 0 weighs 319 lb. per 1,000 ft. (Bare wire value from table in Appendix.)

$$\text{2 wires of No. 0000 } 2 \times \frac{400}{1{,}000} \times 641 = 513.\ \text{lb.}$$

$$\text{3 wires of No. 0 } 3 \times \frac{400}{1{,}000} \times 319 = 383.\ \text{lb.}$$

$$\text{Saving in weight of copper} = 130.\ \text{lb.}$$

VECTOR ADDITION

In the preceding chapter, we discussed the addition of resistance and reactance to give impedance and of active power and reactive power to give total power. These components are added together at right angles, so that a simple numerical addition is not possible. Mathematically, functions of the angles and trigonometric values are used in these calculations. For most practical work, and also as a check on mathematical solutions, graphical addition of the vectors may be used for combining these components.

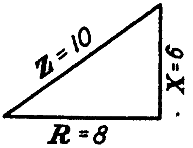


FIG. 45.—Addition of resistance and reactance to give impedance.

Another method is the use of a rule or theorem of geometry that the square of the hypotenuse of a right-angled triangle equals the sum of the squares of the two other sides. The impedance, for example, is then equal to the square root of the sum of squares of the resistance and reactance values. In Fig. 45, resistance equals 8 ohms and reactance equals 6 ohms. Then, if

$$Z^2 = R^2 + X^2, \qquad Z = \sqrt{R^2 + X^2}$$

and

$$Z = \sqrt{8^2 + 6^2} = \sqrt{64 + 36} = \sqrt{100}$$
$$= 10 \text{ ohms}$$

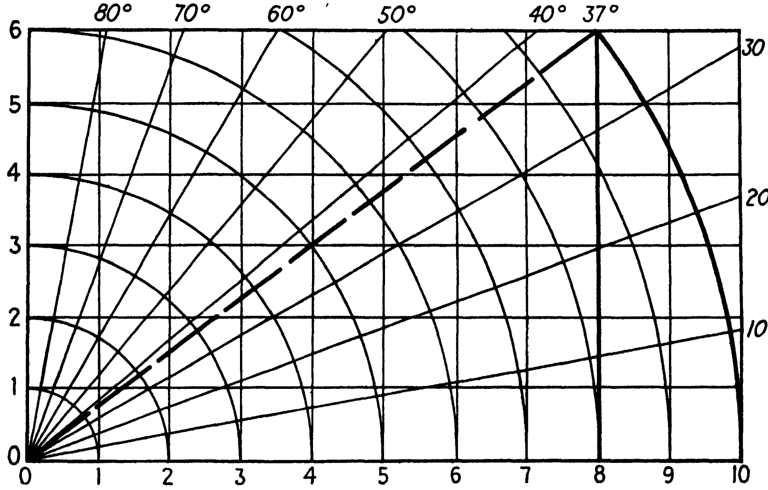


Fig. 46.—Chart for graphical solution by vector addition. Example: 8 on horizontal scale plus 6 on vertical scale equals 10 at angle 37 degrees.

This is solved graphically by drawing the lines for R and X to a scale and measuring the line for Z at this scale. To assist in this method, a chart can be used, in which values are marked on four scales. A chart of this kind is included in the Appendix. The scales are:

1. Horizontal or "real" values.
2. Vertical or "imaginary" values.
3. Polar (arcs of circles) values.
4. Angle (radial lines from 0) values.

Figure 46 shows the application with the values of R equals 8 ohms and X equals 6 ohms. From the value of 8 on the horizontal scale, go up to the line 6 on the vertical scale. From this intersection, follow the arc of circle line to a scale and read the value, in this case, 10. We can also note the angle of Z with R, by following the radial line through the intersection, to the angle scale, in this case, 37 degrees.

A shorthand method of writing these values is to indicate the vertical values by the letter j and to show the angle after the total values. This example is then written

$$8 + j\,6 = 10\underline{/37^\circ}$$

The reverse process is used to find the components of a vector. For 10 at 37 degrees, we follow the arc from value 10 to the radial or angle line of 37 degrees. From this intersection, read down to the horizontal scale, value 8, and left to the vertical scale, value 6. This is written

$$10/37^\circ = 8 + j\,6$$

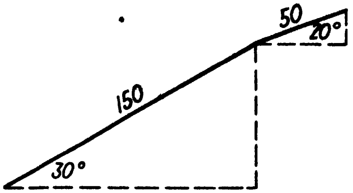


FIG. 47.—Addition of two vectors: 150/30° + 50/20°.

These quantities can be added and subtracted by adding or subtracting the horizontal and the vertical components. Figure 47 shows the addition of 150 at 30 degrees and 50 at 20 degrees.

$$\begin{aligned} 150/30^\circ &= 130 + j\,75 \\ 50/20^\circ &= 47 + j\,17 \end{aligned}$$

The horizontal component of 150 at 30 degrees, 130, is added to the horizontal component of 50 at 20 degrees, 47,

130 + 47 = 177, horizontal component of the resultant vector.

The vertical component of 150 at 30 degrees, j 75, and the vertical component of 50 at 20 degrees, j 17, are added

j 75 + j 17 = j 92, vertical component of the resultant vector.

With a horizontal component of 177 and a vertical component of j 92, the resultant vector is, from the chart, 200 at 27½ degrees

$177 + j\,92 = 200\underline{/27\tfrac{1}{2}^\circ}$, the vector sum of $150\underline{/30^\circ}$ and $50\underline{/20^\circ}$

Example: To add: 120 volts at 37 degrees plus 10 volts at 20 degrees

$$\begin{array}{lrl}
\text{From chart,} & 120\underline{/37^\circ} = & 96.0 + j\ 72.0 \\
 & 10\underline{/20^\circ} = & \underline{\ \ 9.4 + j\ \ 3.4} \\
\text{Add components,} & & 105.4 + j\ 75.4 \\
\text{Resultant vector,} & & = 129/35^\circ \text{ volts}
\end{array}$$

To Subtract: 120 volts at 37 degrees minus 10 volts at 20 degrees

$$\begin{array}{lrl}
 & 120\underline{/37^\circ} = & 96.0 + j\ 72.0 \\
 & 10\underline{/20^\circ} = & \underline{\ \ 9.4 + j\ \ 3.4} \\
\text{Subtract components,} & & 86.6 + j\ 68.6 \\
\text{Resultant vector,} & & = 110/38^\circ \text{ volts}
\end{array}$$

The chart included in the Appendix has scales, 10, 20, etc., up to 200. This will serve directly also for numbers 1, 2, etc., to 20, or 200 to 2,000, by moving the decimal point—care being taken always to reverse the operation in the answer. For example, to read 13.9 + j 5.0 it is necessary to actually read 139. + j 50. equals 148. at 20 degrees. The value we are after is, then, 14.8 at 20 degrees.

For some intermediate figures, it will be necessary to divide the component values by 2 to have them fall on our chart, then multiplying the answer by 2. For example, 240 + j 50 can be read on the chart as 120 + j 25 (each figure being divided by 2) and the resultant read as 122.5 at 12 degrees. This is multiplied by 2, giving 245. at 12 degrees.

Power Factor Angle.—Another use of this chart is to find the angle corresponding to a given power factor. The arc line for value 100 is used for this purpose, representing 100 per cent, or unity. We have noted that the power factor depends on the angle between voltage and current vectors. For convenience, the load current is taken as a reference and is measured along the horizontal scale. Load voltage is at an angle to this, depending on the load power factor. The angle 37 degrees corresponds to power factor 80 per cent, and it is found by following the arc of 100 to its intersection with the line from 80 on the horizontal scale. Other examples include (check on the chart): power factor 70 per cent, angle 45 degrees; power factor 90 per cent, angle 26 degrees.

DESIGN OF LINES HAVING REACTANCE

In Chap. V, we considered the determination of wire size and voltage drop, for lines in which the inductive reactance was negligible, involving resistance only. In the examples, power factor was not considered. With the components and the chart explained and available as a tool, we can now proceed to solution of practical line problems where reactance is a factor and in which the load power factor is not unity.

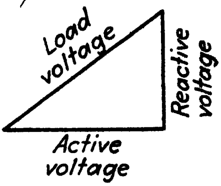


FIG. 48.—Addition of active and reactive components of load voltage.

Load voltage may be considered to have two components, corresponding to the two components of power, active and reactive. The active component of voltage and the current are in phase, and the magnitude of the reactive component is determined from the power factor of the load. This is shown in Fig. 48.

Current in the supply circuit produces two components of voltage drop, one due to resistance and the other due to inductive reactance in the circuit. The active voltage and the resistance drop are added to give the total of one component of the sending voltage. Reactive load voltage and reactive voltage drop are added to give the total of the reactive component of the sending voltage. The total of these components is shown in Fig. 49.

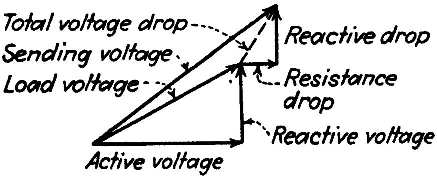


FIG. 49.—Addition of the resistance and reactive voltage drops to the load voltage to give sending voltage.

Example: One-phase, 240 volts, 50 kw. 75 per cent power factor. Find sending voltage if R is 0.05 ohm and X is 0.09 ohm.

$$\text{Solution: } I = \frac{50{,}000}{240 \times 0.75} = 278 \text{ amperes}$$

$$IR = 278. \times 0.05 = 13.9 \text{ volts, resistance drop}$$

$$IX = 278. \times 0.09 = 25.0 \text{ volts, reactive drop}$$

Total drop is, then, 13.9 + j 25.0.

For 75 per cent P.F., the angle is 41 degrees (from the chart). Load voltage is 240 at 41 degrees = 181.0 + j 158.0, and to this are to be added the two components of voltage drop, to give the sending voltage.

Sending voltage:

$$\begin{array}{ll} \text{Load voltage, } 240\underline{/41^\circ} & = 181.0 + j\,158.0 \\ \text{Voltage drop} & = \underline{13.9 + j25.0} \\ \text{Add} & \ 194.9 + j\,183.0 \\ & = 267/43^\circ \end{array}$$

Sending voltage is, then, 267 volts at 43 degrees, or 73 per cent P.F.

Three-phase lines are, in general, considered as *three one-phase* lines, using voltage from phase to neutral. Resistance and reactance are taken for *one wire*, and the drop, regulation, losses, etc., found for each. It is usual to neglect the effect of current in the neutral of a four-wire line and to figure it as though it is a three-wire line. If the loading is unbalanced, the current may be taken as average of the three.

Spacing.—With three wires, an average, or effective, spacing is used to determine the inductive reactance value. This is found as the cube root of the product of the three distances between the three wires. For example, with a horizontal wire arrangement, 2 ft. between one outside wire and the center wire and 4 ft. 4 in. between the other outside wire and the center wire, the spacing between outside wires is 6 ft. 4 in. and their product is

$$24 \times 52 \times 76 = 95{,}000.$$

The cube root is 46 in., *effective* spacing.

Example: Find sending voltage and regulation of a line 5 miles long having 1,500 kw. at 80 per cent power factor. Voltage is 13,200, three-phase. Wire is No. 0000 copper. Spacing is horizontal, 2 ft., 4 ft. 4 in. between wires.

Solution: Effective spacing (from above) is 46 in.
Resistance $R = 0.0505$ ohm per 1,000 ft.
Inductive reactance $X = 0.127$ ohm per 1,000 ft.

$$R \text{ per wire} = 5 \times \frac{5{,}280}{1{,}000} \times 0.0505 = 1\ 33 \text{ ohms}$$

$$X \text{ per wire} = 5 \times \frac{5{,}280}{1{,}000} \times 0.127 = 3.35 \text{ ohms}$$

$$\text{Current per wire, } I = \frac{1{,}500{,}000}{\sqrt{3} \times 13{,}200 \times 0.80} = 82. \text{ amperes}$$

Resistance drop, $I \times R = 82 \times 1.33 = 109$ volts

Reactance drop, $I \times X = 82 \times 3.35 = 275$ volts

Voltage phase to neutral $= \dfrac{13{,}200}{\sqrt{3}} = 7{,}630$ volts

For 80 per cent power factor, the angle between load voltage and load current (from the chart) is 37 degrees. Now, on the chart, find intersection of arc from 7.6 (7,630) and angle 37 degrees. Read horizontal and vertical scales, 6.1 and 4.6.

Active load voltage is, then, 6,100 volts, and reactive load voltage is 4,600 volts

Next step is to add the active component of load voltage to the resistance component of voltage drop

$$6{,}100 + 109 = 6{,}209 \text{ volts}$$

and reactive component of load voltage to reactive component of voltage drop

$$4{,}600 + 275 = 4{,}875 \text{ volts}$$

giving the two components of the sending voltage; 6,209 and 4,875

From 6 2 on horizontal scale, go up to 4.9 on the vertical scale, and read arc scale value from the intersection and also the angle

$$7.9 \text{ at } 38 \text{ degrees, or } 7{,}900/38^\circ \text{ volts}$$

This is the sending voltage, phase to neutral, and phase to phase volts

$$7{,}900 \times \sqrt{3} = 13{,}650 \text{ volts}$$

Summarizing the steps from this explanation,

Resistance drop = 109 volts

Reactance drop = 275 volts

Active voltage (7,630 volts at 80 per cent P.F.) = 6,100 volts

Reactive voltage = 4,600 volts

$$\begin{array}{ll}
\text{Load voltage} & = 6{,}100 + j\,4{,}600 \\
\text{Voltage drop} & = \underline{\;\;109 + j\;\;275} \\
\text{Sending voltage} & = 6{,}209 + j\,4{,}875 \\
 & = 7{,}900\underline{/38^\circ} \text{ phase to neutral}
\end{array}$$

Sending voltage phase to phase = $7{,}900 \times \sqrt{3}$ = 13,650 volts
Load voltage = 13,200 volts
Drop = 450 volts

$$\text{Regulation} = \frac{450}{13{,}200} = 3.4 \text{ per cent}$$

POWER FACTOR IMPROVEMENT

In the preceding chapter, we considered the general subject of power factor and the methods of its improvement. Now, we want to go into more detail in the calculations required for determination of capacitor size. The purpose of such improvement is reduction of current. There are two principal economic reasons to justify the expenditure for this improvement:

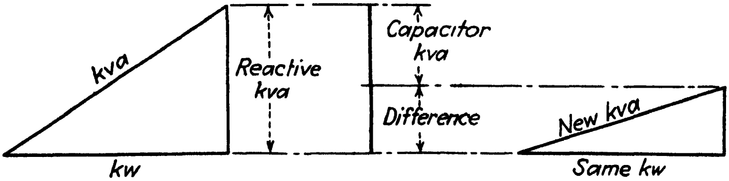


FIG. 50.—Graphical representation of power factor improvement.

1. In the one case, existing facilities for transmission, transformation, and distribution can be used more effectively by reduction of kilovolt-ampere load for a given kilowatt load. Postponement of larger expenditures for additional substation and feeder capacity can be compared directly with the investment required for such correction of power factor.

2. In the second case, voltage conditions may be the justification, and the cost of power factor correction can be compared directly with the cost of increasing copper size, additional feeders, regulation, or other means.

Calculations can be made in several ways, and, to simplify the work, various charts and graphs have been developed. Fundamentally, to raise power factor, we add another load to the line. This load is, however, reactive in the opposite direction. It subtracts from the reactive component of the load to give a smaller total reactive component on the line. Since kilovolt-amperes equals the vector sum of kilowatts and reactive-kilovolt-amperes, the kilovolt-amperes is reduced by this reduction of reactive-kilovolt-amperes, as shown in Fig. 50.

These problems can be solved with the aid of the chart we have used for voltage drop calculations, as illustrated in these examples.

Example: 55 kw., one-phase, 240 volts, 60 per cent P.F. Determine power factor correction necessary to reduce current to 285 amperes.

Solution: $I = \dfrac{55{,}000}{240 \times 0.60} = 380$ amperes

For power factor of 60 per cent the angle is (from chart) 53 degrees

The load current has two components:

$$380/53^\circ = 230 + j\,300 \text{ amperes}$$

At the new power factor, the active component will still be 230 and the new total amperes is to be 285 amperes.

Our next step is to determine the reactive component to give this total. On the chart, we follow vertical line up from value of 230 on the horizontal scale, until we reach the arc line for 285. At this intersection, we read 170 on the vertical scale and 37 degrees on the radial scale. The new current is, therefore,

$$285/37^\circ = 230 + j\,170 \text{ amperes}$$

At 53 degrees, we had 300 amperes in the reactive direction, and at 37 degrees we have 170 amperes. The correction is then

$$300 - 170 = 130 \text{ amperes}$$

This current, 130 amperes, must be drawn by the capacitor to reduce total current to 285 amperes. At the new angle, 37 degrees, the power factor will be 80 per cent.

Example: 900 kva. at 81 per cent P.F. Increase to 95 per cent P.F.

Solution: From the chart, 81 per cent P.F. is 36 degrees angle, and 95 per cent P.F. is 18 degrees angle.

$$900\underline{/36^\circ} \text{ kva.} = 730 \text{ kw.} + j\,525 \text{ rkva.}$$

This 730-kw. load is to have P.F. = 95 per cent or angle 18 degrees.

From the chart, we shall then have 240 rkva.

The difference between 525 rkva. and 240 rkva. = 285 rkva. of capacitors required.

The new kilovolt-amperes will then be

730 kw. + j 240 rkva. = 770 kva.

These conditions are summarized in the diagram of Fig. 51.

Reduction of load by power factor improvement is often an alternative to other changes that may be made to increase the useful capacity of a line or transformer bank. In the following example, the transformers are already fully loaded and we want to add load. Cost of capacitors or other means of reducing the reactive load should be compared with cost of changing the transformers. The improvement needed might also be obtained by the use of a synchronous motor for the new load or by replacing one of the present motors that is contributing to the lagging component of power.

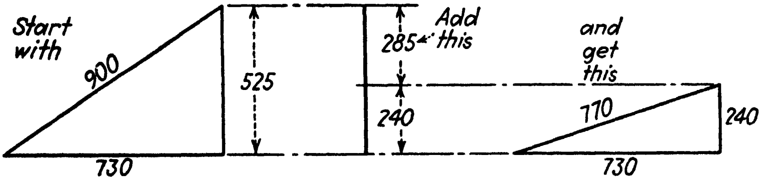


FIG. 51.—Graphical solution of capacitor application example.

Example: A plant with 500-kw. demand is supplied by a 750-kva. transformer bank. We want to add 150 hp. of load, which we estimate will mean another 100-kw. demand (at the same power factor). A power factor check shows 65 per cent P.F. at the 500-kw. demand; therefore the bank is already slightly overloaded. How much reactive kilovolt-ampere should be installed along with the new load to allow the present bank to continue without overload? What will the new power factor be? What size of bank will be required if no correction is made?

Solution: With 500 kw. at 65 per cent P.F. (49°), the reactive component is, from chart, 580 rkva.

500 kw. + j 580 rkva. = 770 kva.

New demand is to be 500 kw. + 100 kw. = 600 kw. At the same power factor, 65 per cent, 600 kw. is 920 kva. Its reactive component is, from chart, 700 rkva.

600 kw. + j 700 rkva. = 920 kva.

But, to limit to 750 kva. with 600 kw.; we find, from the chart, that the reactive component cannot exceed 450 rkva.

Then, 750 kva. = 600 kw. + j 450 rkva.

Correction must reduce the reactive component from 700 rkva. to 450 rkva., to hold the kilovolt-amperes down to 750, with 600-kw. load.

Therefore, 700 − 450 = 250 rkva. is the correction.

With 600 kw. + j 450 rkva., angle is 37 degrees, and power factor is 80 per cent.

If no correction is made, load will be 920 kva. and a bank with capacity of 1,000 kva. will be required. The cost of making this change should be compared with cost of 250 rkva. of power factor correction.

Excessive voltage drop in a supply line may be the result, if we neglect these design checks. The following example is an actual case. A 1,500,000-c.m. wire line was installed on racks along a building to supply a three-phase power load about 500 ft. from the transformer. The flat spacing was 9 and 18 in. between wires, giving effective spacing of 12 in. With full load, the supply voltage was 257 and the load voltage was 190, a drop of 67 volts.

A current reading showed 1,140 amperes, and a power factor check showed 50 per cent. By neglecting the effect of the low power factor and the relatively very high inductive reactance, it was thought that the drop should be only 4 volts. The total resistance was 0.0037 ohm per wire and the total reactance 0.0355 ohm per wire.

It was recommended that either (1) the rack line be replaced with a cable or conduit line to reduce the spacing and resulting inductive reactance or (2) the power factor be raised to 75 or 80 per cent at the load. Either of the measures would reduce the drop to about 35 volts. The alternative was extension of the primary line and relocation of the transformer.

SUMMARY AND PROBLEMS

In this and the preceding two chapters, we have considered the fundamentals of electrical calculations. The graphical or chart method outlined in this chapter is limited in accuracy, but it fulfills the double purpose of assisting us to visualize the elements and serving for the usual practical design calculations. Ordinarily, we must start with figures that are not exact for the conditions, and answers to the exact volt are not practical or necessary.

These fundamentals are the tools that serve for usual work, much as pliers, hammers, and shovels serve for field work. For more exact tool work, we need calipers, gauges, etc., and, for more exact calculations, we need trigonometry and other mathematics. But the fundamentals are the basis for the exact methods.

Power factor improvement may not occupy the place of relative importance that the space given to it here, compared with voltage drop calculations, would indicate. Knowledge and use of power factor in practical problems are very essential, however, and the method of improvement is used to emphasize the importance of accounting for this factor.

Problems:

1. Find the value of impedance Z for each case of Prob. 5, page 78.

2. Find the current with a 200-kw. load at 480 volts, under these conditions:

(*a*) One-phase, 100 per cent P.F.
(*b*) Three-phase, 100 per cent P.F.
(*c*) One-phase, 75 per cent P.F.
(*d*) Three-phase, 75 per cent P.F.

3. Find the voltage drop of a line supplying the load of Prob. 2 with condition (*d*) if distance is 200 ft. and the minimum size of wire with weatherproof insulation is spaced 10 in. effective.

4. Find the sending voltage and regulation of a line 3 miles long, supplying 1,000 kw. at 80 per cent P.F. Voltage is 4,160 volts, three-phase. Wire is No. 00, spaced 2 ft., 4 ft. 4 in. horizontal. (NOTE: See Prob. 1, Chap. X, also.)

5. A 4,160-volt three-phase primary feeder has 262 amperes peak load per phase. The substation regulators and cable are rated 250 amperes. Present power factor is 65 per cent. It is expected that load growth in the next year will be 10 per cent. How much capacitor reactive kilovolt-amperes must be added to allow this growth and hold the current to within the rating of 250 amperes? What will the improved power factor be?

6. The minimum load on this feeder is 85 amperes at 48 per cent P.F. If we do not want power factor to become *leading* (that is, the power factor is to be unity at minimum load), what is the maximum reactive kilovolt-ampere of capacitors that can be added? With this reactive kilovolt-ampere load, what would the power factor be at the present peak load?

7. With conditions given in the example preceding the summary, check the recommendations for reduction of the excessive voltage drop to 35 volts.

CHAPTER VIII

TRANSFORMERS

The transformer is the most important and essential factor in effecting economical and wide distribution of electrical energy. It is the means by which power can be transmitted at high voltages, stepped down to lower voltages for general distribution, and further reduced to values suitable for direct use by lights and appliances. Transmitting and distributing at relatively high voltages means that the current and the wire size required are correspondingly small. Consequently, the mechanical requirements and the electrical losses and voltage drop in the lines can be kept at practical values. The diagram of the typical electric system shows how the divisions are built around the transformers.

The practical radius of distribution with the direct current system was less than a mile. This led some engineers to consider means of using higher voltages, which, in turn, led to the consideration of transformer development. The original transformer had been made by Faraday, about 1831, in connection with his other studies in the field of electromagnetic possibilities. He wound primary and secondary coils of wire on an iron ring. Later experimenters found that the characteristics were improved by using iron wire instead of the ring, which led to the laminated core. The early development of our present type transformer was based on the work of Gaulard and Gibbs in England. Their patents were purchased in 1885 by George Westinghouse, who sponsored the early work of William Stanley. During the same period, Elihu Thomson was working independently toward the same end.

In the first alternating current distribution system, Stanley's transformers were used. The work of these men and their contemporaries has remained the basis for transformer design, and, although later developments have greatly reduced the losses and improved the operation, the principles and general idea have remained the same. The most important addition

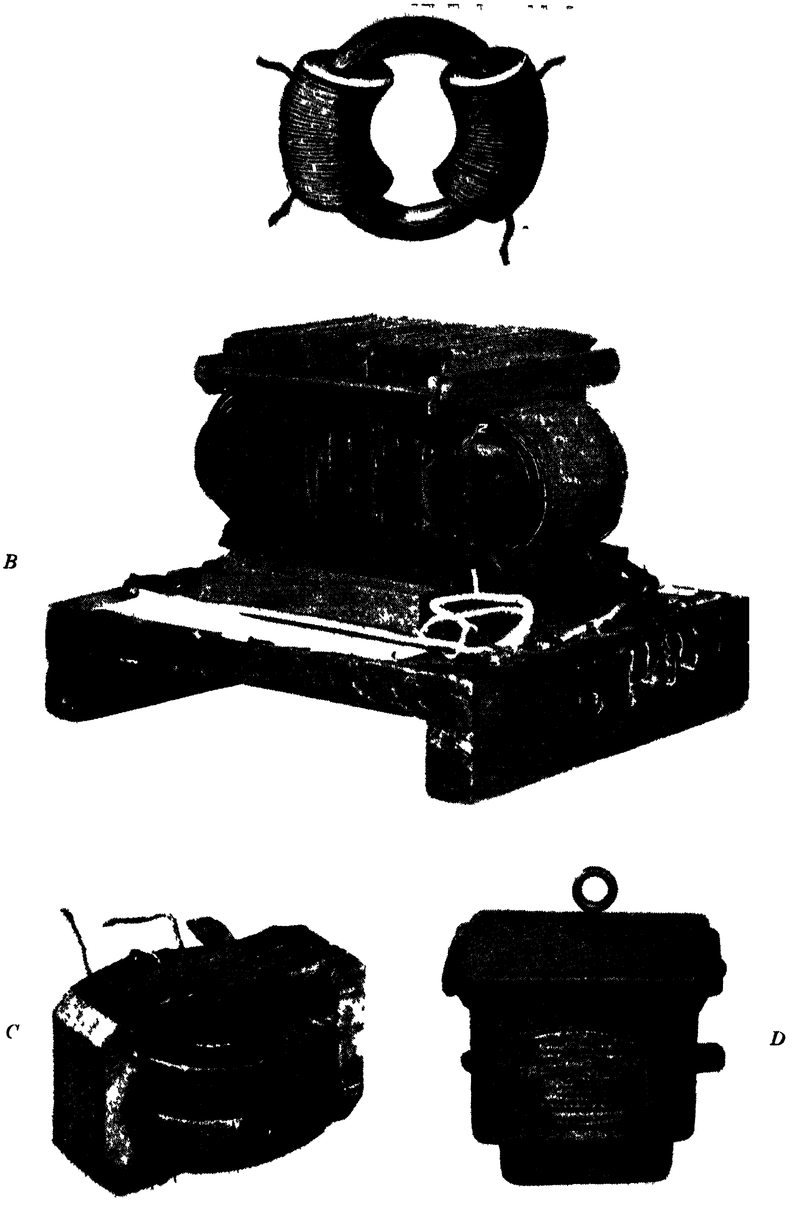


FIG. 52.—Early development of the transformer. *A*, Faraday experimental model—1831; *B*, Stanley original model—1885; *C*, one of the first commercial models—1890; *D*, case for 1890 transformer.

to the core and coil design was the use of oil, first tried in 1887, as an insulating and cooling medium. Figure 52 pictures several early type transformers, and Figs. 53, 54, 55, and 56 show some examples of modern design.

These very vital links in the electric systems also represent one of the largest items of cost and investment, and their proper design and application are, therefore, especially important. From both an economic and an operating standpoint, the selection of the correct transformers, based on the characteristics of the load served, is of primary importance. Distribution operators are not directly concerned with the transformer design details, but to a large extent they must determine and select the general features of the design. Thus, the voltage ratio is directly a function of application. The most economical loss values are determined by other system costs and by load characteristics, and mechanical construction must be closely correlated to line and installation practices.

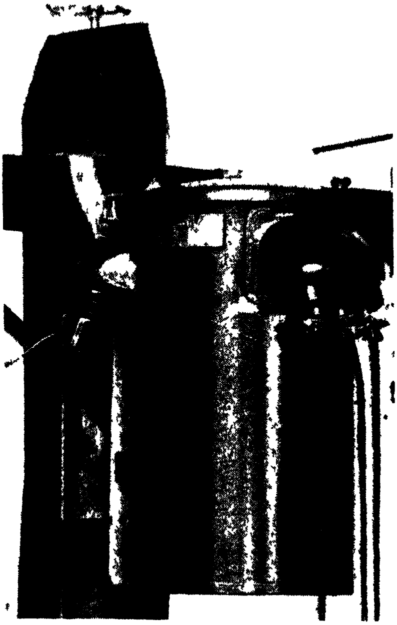


FIG. 53.—Distribution transformer for pole mounting. 10 kva. 2400–120/240 volts.

Principle of the Transformer.—Whether the transformer is of the smallest size to serve a single residence or of the largest capacity in one of the largest substations, its principle is the same. In addition, this same principle is, as we have noted in Chap. VI, the basis of design of motors and generators. It is also used in the design of meters, relays, and other parts of the complete electric system.

Alternating current, passing through a winding or coil of wire, sets up an alternating magnetic field around the coil. In the transformer, two windings are mounted on an iron core. Current passing through one winding induces a current in the second winding through action of the magnetic field, which is greatly assisted by the iron core. Similarity to the generator action should be noted, with this very important difference—there is no mechanical movement in the transformer. The cutting of magnetic lines of force, which is supplied by movement of the conductor in the generator, is obtained by "collapsing" and reversal of the magnetic flux or field in the transformer. This magnetic reversal is caused by the reversal of current every half-cycle in the alternating current circuit.

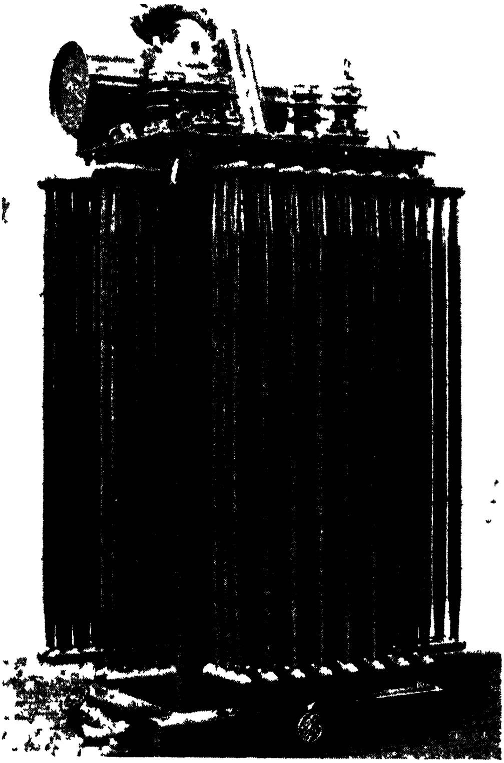


FIG 54 —Large power transformer 1 000 kva. 13,200–2,300 volts, single-phase.

Relative current and voltage values of the two windings are a function of the relative number of turns or coils of the windings. For example, in a 2,400- to 240-volt transformer (voltage ratio 10 to 1), there are ten times as many turns of wire in the 2,400-volt winding as there are in the 240-volt winding. Since the volts times amperes input is equal to the volts times amperes output (losses being neglected), the current ratio is the inverse of the turn and voltage ratio. For this 2,400- to 240-volt transformer, if the load current is 100 amperes at 240 volts, the current at 2,400 volts is 10 amperes.

The transformer principle might be compared with the principle of a beam balance, as shown in Fig. 57. The weight of 100 lb. 10 ft. from the support will balance the weight of 200 lb 5 ft. from the support. That is, 100 lb. times 10 ft. equals 200 lb. times 5 ft. Similarly, for the transformer of the previous paragraph, input volts times amperes equals output volts times amperes, or 2,400 × 10 = 240 × 100

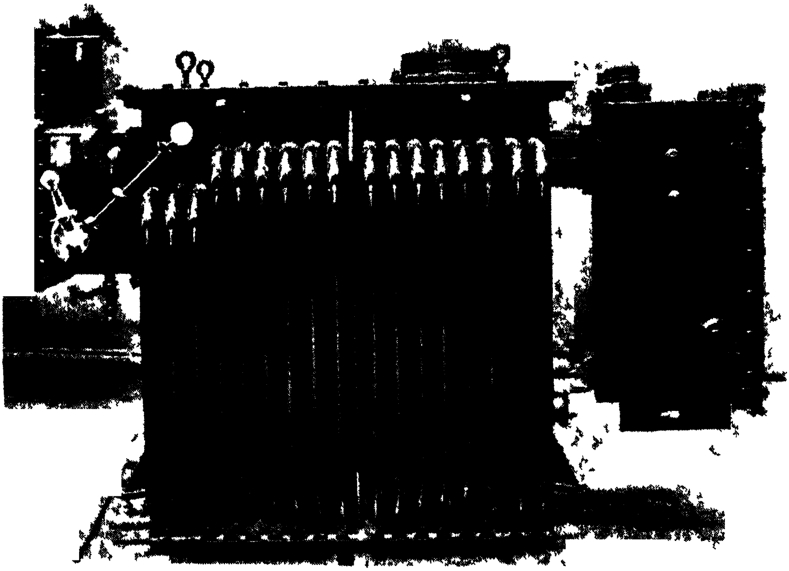


Fig 55 —Three-phase 500-kva. transformer with switches for network supply

It will be noted that the smaller current is in the higher voltage winding and the larger current in the lower voltage winding. Summarizing this and the statement above about the relative number of turns in the winding, the high-voltage winding has a large number of turns of small wire and the low voltage a small number of turns of large wire.

In mechanical construction, a transformer consists of a laminated steel core interlinked by insulated coils of copper wire.

The core is an assembly of thin sheets of special steel. The coils are wound on the legs of the core, and in some designs they are also surrounded by legs of the core. Insulated wire is used in the low-voltage and high-voltage coils, and additional insulation is used between the layers and turns of the wire. Some layers are separated to form oil ducts to permit the circulation of oil for cooling.

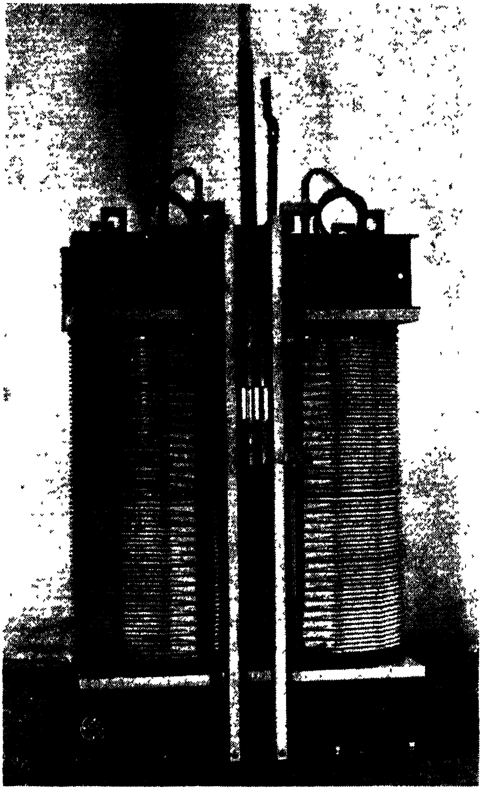


FIG. 56.—Core and coil assembly of 2,500-kva. transformer, 11,000-2,400 volts single-phase.

This assembly of copper and steel is mounted by means of rigid braces in a steel tank, which is then filled with oil. Low-voltage and high-voltage leads to the transformer coils are carried into the transformer case through insulating bushings. The leads may be of flexible wire, or they may be rigid studs with bolt connections.

Distribution transformers are almost universally of the self-cooled type, and the oil plays a very important part in this cooling. Oil circulates through the layers of the coils and around the complete coil and core assembly as it is heated, and it rises to the top and to the sides and walls of the transformer case. As heat is given off and radiated from the case, the cool oil goes to the bottom and again goes through the coil and core assembly to further carry heat. The oil surrounding the windings and leads also has an important part in insulation.

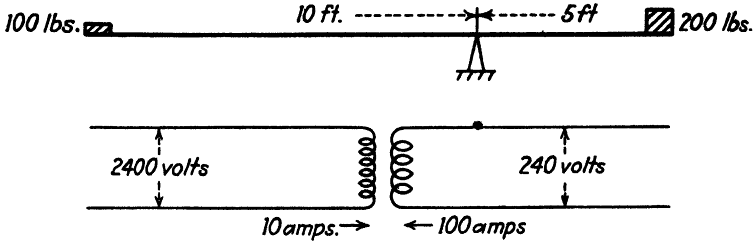


FIG. 57.—Beam-balance analogy of transformer ratio.

Rating and Ratio.—Transformer ratings have been largely standardized through cooperative efforts of electrical engineering bodies, the manufacturers, and the utilities. The capacity or output rating of a transformer is given in thousands of volt-amperes, or kilovolt-amperes. It is based on the load that it will carry continuously, without having a temperature rise greater than 55 degrees centigrade above a 30-degree centigrade average ambient temperature. Actually, transformers may carry considerably more load than their rating, when such overloads are for short periods of time or when the outside temperature is low. This fact is important in usual loading practices, and it is discussed in a following section of this chapter.

The voltage ratio of the transformer is determined with no load on the secondary or output side. With the particular voltage ratio used in the example above, transformation is ordinarily down, from 2,400 to 240 volts, but it would work equally well in the other direction, from 240 to 2,400 volts. The input side is referred to as the primary and the output as the secondary. Voltage ratings are written with primary voltage first and secondary voltage last, separated with a dash —. The voltages obtainable are separated by a slant; thus, a 2,400—

120/240-volt rating means 2,400 volts primary to 120 or 240 volts secondary. This transformer would have 115 or 230 volts secondary with 2,300 volts on the primary, that is, 2,300—115/230 volts.

Taps may be included in either of the windings to provide for operation at voltages differing within a limited range from the standard ratio. The tap leads may be carried to a ratio adjuster with handle through the tank, or the tap terminals may be on a connection block inside the case. These connections can be changed or adjusted only with the transformer out of service and de-energized. They are usually in the high-voltage winding, for example; (1) two 5 per cent taps, or (2) four 2½ per cent taps, below normal, in the high-voltage winding.

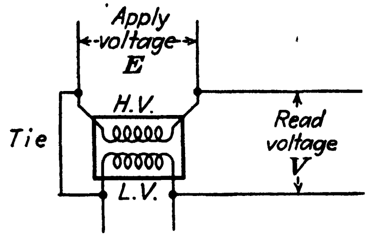


Fig. 58.—Polarity test connections.

With four 2½ per cent below normal taps in the high-voltage winding, the rated secondary voltage may be obtained with a 2½, 5, 7½, or 10 per cent reduction in the primary voltage, if set on the proper taps. Or any of these percentage taps may be used for raising voltage above the secondary rating to allow for drop in the secondary lines. This is considered in a later chapter on Voltage Control.

As an example, a transformer with 5,000 turns in the primary winding could have taps at 2½ per cent of 5,000, or 125 turns, from the end, 5 per cent, or 250 turns, 7½ per cent, or 375 turns, and 10 per cent, or 500 turns. Since the voltage ratio is proportional to the turn ratio of the transformer, the voltage can be changed to the desired value by using the corresponding percentage tap. Thus, a 13,200-volt primary will supply the rated secondary voltage with 13,200 minus 10 per cent of 13,200, or 11,800 volts primary, if connected between the end terminal and the 10 per cent tap. Or a 240-volt secondary can be made to supply 252 volts with the 5 per cent primary tap and rated primary voltage supply.

Tests.—In the following paragraphs and figures, some of the tests made on transformers are outlined. For our present purpose, these are for explanation of the fundamental principles only and are not complete in many of the details of test procedure.

Polarity of a transformer depends on the relative position of the leads or bushings on the transformer case. It does not affect the operation of a single transformer, but it is very important in the connection of transformers in a three-phase bank or for parallel operation. Polarity of a single-phase transformer may be changed by reversing the positions of either the high-voltage or the low-voltage leads. It is determined by the relative instantaneous directions of current in the two windings.

In the polarity test, adjacent terminals or leads of high- and low-voltage windings are connected (Fig. 58). A voltage (usually a low voltage for test) is applied to the high-voltage winding, and voltage is read between the two adjacent free primary and secondary terminals, not connected. If this voltage is *greater* than that applied on the high-voltage winding, then the transformer is *additive;* if *less*, it is *subtractive.* With this test, the secondary voltage is either added to or subtracted from the voltage on the primary—giving the terms additive and subtractive.

Standard arrangement is additive for sizes 200 kva. and smaller, with voltage 7,500 or below, and subtractive if either the size is over 200 kva. or the voltage is more than 7,500 volts. This arrangement has been standard since about 1921.

Insulation.—In addition to the normal voltage on the windings, the lead wires and connections, and bushings, protection for voltages above this level must also be provided. Much research and many tests and experiments in design have gone into this phase of transformer design. We can expect transformers, with a reasonable amount of care, to withstand voltage surges up to the point where lightning arresters, coordinating gaps, and connections to ground can protect them against damage by lightning. Present insulation design is based on careful field and laboratory studies of the voltage surges caused by lightning.

The most important test of transformer insulation is possible only with high-voltage surge impulse generators. These tests have been developed in recent years and are intended to produce stresses in the insulation of the order of those produced by lightning itself. For field and repair shop checks, a dielectric test can be made, with voltage applied between each winding and the tank and between the windings, with connections as shown in Fig. 59.

In the dielectric test, a stress is imposed on the windings and it is not recommended that it be repeated frequently. For field or shop test, 10,000 volts may be used between the high-voltage winding and the low-voltage winding and the case, where the primary rating is 2,400/4,000 volts. Between the low-voltage winding and the case, 4,000 volts may be used for distribution transformers. For higher voltage ratings, these test values are increased, according to recommendations adopted by industry committees. The test voltage is applied gradually, increasing to full value in about one-half to one minute. It is held for one minute and then gradually reduced.

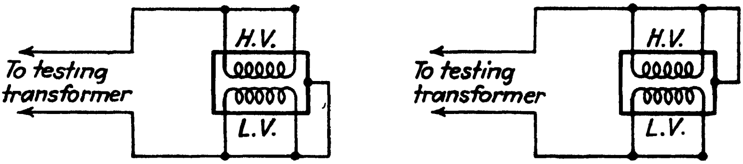


FIG. 59.—Insulation or dielectric test connections.

Insulation resistance tests may also be used to check the insulation condition. These tests are of most value to determine any damage by moisture. The most convenient way is by use of a "megger," a meter reading in megohms (millions of ohms) with energy supplied by a hand-driven magneto. The test may also be made with direct current voltage.

Oil is an important part of the transformer insulation, and its condition is subject to the most change, in service, of any part of the transformer. Frequent oil tests are made where the transformers are large and important, such as those in distribution substations. The same frequency is not, of course, possible or necessary for smaller transformers. Oil level and a visual check of condition should be made periodically.

In the test, a sample is placed in a special cup with 1-in. diameter disk terminals spaced $^1\!/_{10}$ in. apart. Voltage is applied and gradually raised to the breakdown of the oil. This point must be above 22 kv. for standard oil. If it is as low as 16 kv. in service, it should be filtered. Reduction of this test value indicates that moisture, dirt, or other foreign materials are mixed in the oil, and filtering or purifying is necessary to remove them.

Core Loss.—A transformer, connected to the line, draws some energy even though there is no connection made to the output side. This energy is used to magnetize the iron core and is constant for all values of load, or for no load, depending only on voltage being applied to one winding. It is lost energy, as far as useful output from the transformer is concerned. It is also called "no-load" or iron loss.

This loss is determined by energizing either winding at its rated voltage, with no connection to the other winding, and reading watts input. It is usually most convenient to energize the low-voltage winding, with connections as shown in Fig. 60.

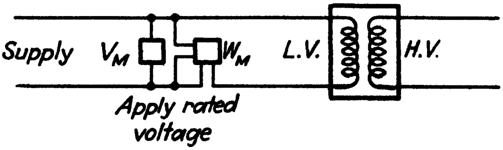


Fig. 60.—Core loss test.

Copper Loss.—When current is passed through the windings of a transformer, a loss takes place the same as in any other circuit. This is the current squared times resistance loss (I^2R) of both the high-voltage and low-voltage windings. The test value of this loss is determined and given in the data for full-load condition. The loss at any other load is, therefore, proportional to the ratio of the squares of the current at this load and at full load. For example, if the full-load current is 10 amperes and the loss is desired at 5 amperes, we find it as

$$\frac{5^2}{10^2} = \frac{25}{100} = \frac{1}{4} \times \text{Full-load loss}$$

The copper loss test is made by connecting a short circuit on one winding and using just enough voltage on the other winding to cause full-load current to flow. Usually it is most convenient to short-circuit the low-voltage leads and apply voltage to the high-voltage winding. The voltage required is a small percentage of the rated primary voltage of the transformer. The watts input, with full-load current flowing, is then read on a wattmeter (Fig. 61).

Regulation.—Just as in any other circuit, there is a drop in voltage in the transformer, due to the resistance and the inductive reactance in the windings. This drop is expressed as a percentage of the rated load secondary voltage. For example, a 3 per cent regulation means that a 2,400—240-volt transformer delivers 240 minus 3 per cent, or 7.2 volts, which equals 232.8 volts, with full load, and with 2,400 volts on the primary.

Drop due to impedance of the transformer can be measured at the same time the copper loss test is made. In Fig. 61, voltage impressed on the primary to cause full-load current to flow will be a percentage of the rated voltage of the transformer. For accurate results, these tests are subject to correction for temperature and other factors. Further reference to transformer impedance and regulation will be found in Chap. XI.

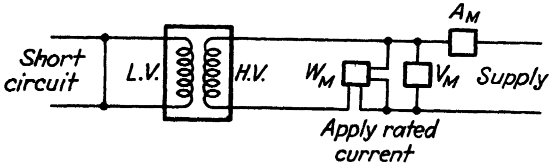


FIG. 61. —Copper loss test

LOADING OF TRANSFORMERS

We noted in a previous paragraph that the capacity rating of a transformer is the load it will carry continuously without exceeding a specified temperature. The temperature rise in the transformer is due to the heat caused by the losses, and there is a time lag between the start of heating and reaching of maximum temperature. When load is applied to the transformer, the heating starts, but the metal absorbs some, and the oil movement carries heat to the tank walls where it is dissipated to the outside air. The rise is gradual, and with a constant load several hours may elapse before the temperature reaches a maximum and becomes constant.

It is this maximum temperature within the transformer windings that determines the safe loading. This limit is less than the point at which the winding insulation would begin to deteriorate and finally to fail. The limit of safe temperature in the hottest part of the windings is just below the boiling point of water (55 degrees rise above an ambient or outside temperature of 30 degrees, plus an allowance of 10 degrees, is 95 degrees, centigrade). Actually, operation even at a temperature higher than this limit may not mean immediate destruction, but it does result in deterioration. After continued operation at excessive temperatures, failure will occur, or the insulation will be more susceptible to breakdown from a voltage surge caused by lightning.

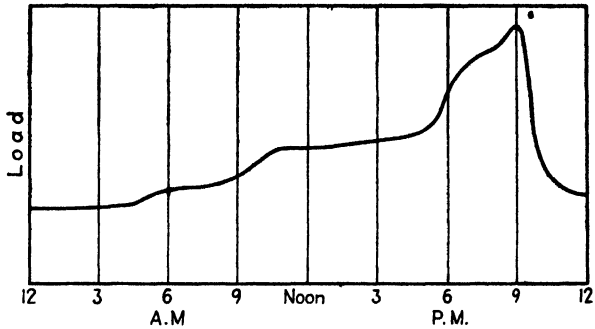


FIG. 62.—Load curve for transformer serving outlying commercial area. Winter Saturday.

The point to be emphasized is that the load that a transformer can carry is not necessarily its rating. It depends also on the temperature of the air surrounding the transformer, the time the load is maximum, and the load that has been carried previous to the maximum. Economical operation of distribution transformers requires, therefore, a knowledge of the load characteristics and other conditions, as well as of the transformers themselves.

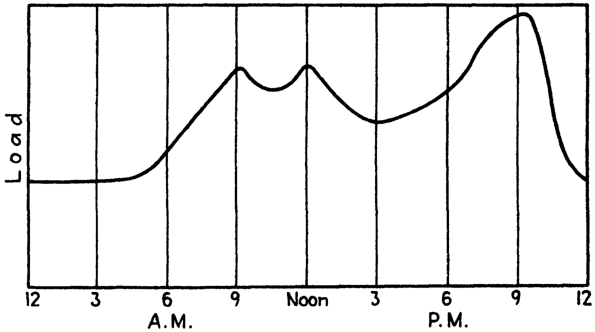


FIG. 63.—Load curve for transformer serving residential load with ranges and refrigerators in every home.

This subject has been given considerable attention by several groups and particularly by members of the Transmission and

Distribution Committee of the Edison Electric Institute. Extensive tests have been made, and must be continued, to determine the characteristics of loads. In general, characteristics of residential and commercial loads have changed much more in recent years than have those of industrial loads. Transformers serving industrial loads, and often large commercial loads, must usually carry the maximum load over a longer period of time than do the transformers for residential and small commercial loads. The curves of Figs. 62 to 65 show the varying character of the loads carried by transformers in residential areas.

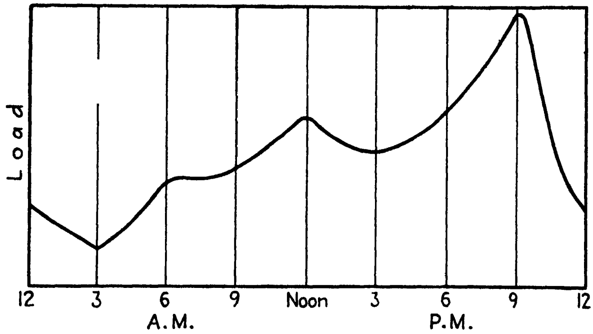


FIG. 64.—Load curve for transformer serving residential customers without ranges or refrigerators. Compared to group of Fig. 63, the per customer kw.-hr. used is 1/6 and the demand 1/5.

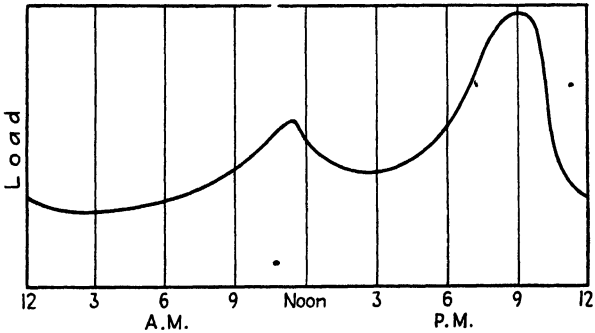


FIG. 65.—Load of medium usage residential customers. All have refrigerators, but no ranges.

From a great many tests of this kind, and also of the heating effects on insulation life, curves such as shown in Fig. 66 can be drawn. They show the limiting load for any month of the year for each size transformer with residential loads of lighting, refrigeration, and small appliances but not including ranges. An entirely different set of curves is necessary where range load saturation is high.

A general conclusion from these studies is that, with the types of residential loads commonly served, peak loads of 120 to 160 per cent of the transformer rating may be carried. These peak periods seldom exceed 1 hr., with a total of 3 hr. of maximum loading approaching the peak in value.

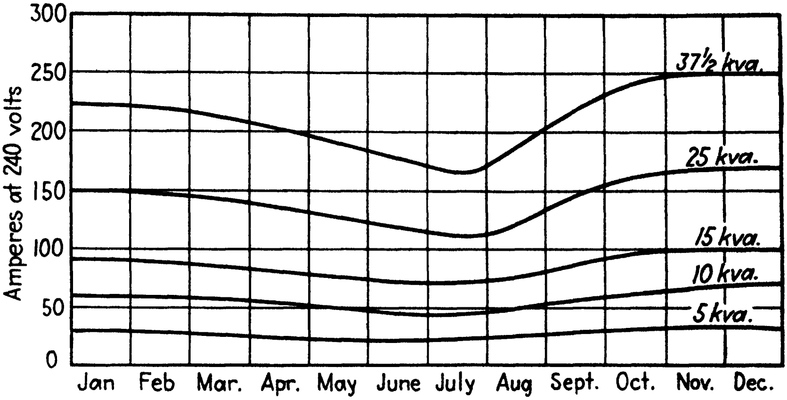


FIG. 66.—Chart of transformer size for current reading during any month of year. For residential load areas.

An important factor in the consideration of transformer application is the rate of growth of load. It is not economical to install a transformer that is just large enough to carry the present load, if the load can reasonably be expected to grow to such an extent that it would be necessary to make a change within a short time. On the other hand, the opposite extreme is not economical. For example, it may not be economical to install a 15-kva. transformer if a 10-kva. size would carry the load for several years. The curves referred to above show a 10 per cent per year growth in the load.

Although the economy of such careful consideration may not be so apparent in the case of a single transformer, it can amount to a great deal when applied to several thousand transformers on a large distribution system. In fact, it may well be that the effective application of distribution transformers offers one of the greatest opportunities for use of a clear understanding of the fundamentals of distribution and of the loads served.

Field Testing of Transformer Load.—For large transformer installations in substations, it is usual practice to have meters for measuring the load carried, and these measurements are also important for other purposes in load analysis. For the larger industrial loads, demand metering is general for billing purposes. In these cases then, determination of transformer load is incidental to other uses of the data. Economy of application, cost to change transformers, and usually longer periods of maximum loading all lead to the practice of using capacity rating equal to, or higher than, the demand.

From the standpoint of number, total kilovolt-amperes, and investment, the smaller transformers installed on poles or platforms, or in vaults, in the average distribution system exceed the larger substation and large industrial service transformers. These transformers, serving residential, commercial, and smaller industrial customers, require periodic load checks to ensure economical operation. Underloading results in loss because of the unnecessary investment. Overloading leads to deterioration of the insulation and failure of the transformers, necessitating definite costs for replacement and possible loss of good will due to outages to the customers served.

Factors to be considered include rate of load growth, cost to change transformers, load characteristics, as peak value, duration, and time, in addition to engineering information on transformer characteristics. The curves of Fig. 66 show the application of these data for transformer size determination from one study of this kind. Routine load checking or testing is followed on a periodic basis, the time between tests and the method used varying with local conditions. An outline of the methods in use follows:

A. Periodic Field Tests

1. Spot readings with split-core current transformers and ammeter are the most widely used. The current transformer is placed around the leads of the distribution transformer and an ampere reading of load obtained.

2. Indicated peak demands may be obtained for a day or a several day period, with standard demand meters or special test meters.

3. Oil temperature indicators may be installed temporarily for the test.

4. Graphic chart meters may be installed to obtain a complete load curve during the test period.

5. Permanently installed oil temperature indicators may be included on the transformers, so that periodic readings can be obtained, giving maximum load indication.

6. Transformers may be equipped with protective devices to prevent overloading by opening the circuit or to give a visible warning of loading beyond a set value.

Of these methods, (1) has the advantage of being low in cost, requiring only one trip, and a minimum of equipment. It has the disadvantage of reading only a single load condition, which may be reliably obtained only during a few hours of the day. Methods (2), (3), and (4) require two trips, to install and later to remove the equipment, but have the advantage of a check over a longer period of time. Methods (5) and (6) require investment on each transformer, in addition to the single-trip check, although (6) may reduce this checking expense by not requiring such frequent inspection.

B. Load Estimating Methods

1. Estimates of load may be made from service records and maps, by applying average demands per customer or per major appliance.

2. Kilowatt-hour consumption records may be summarized for the group of customers served by each transformer, with a check of charts and loading factors to estimate the demand.

3. Billing demand records may be available for industrial and larger commercial loads.

On any large system, several of these load supervising methods may be in use to meet the variety of conditions encountered. The largest variables between systems are the load characteristics, and the basis for the load testing should be correlated with more complete load checks on typical installations. That this careful routine is justified is evident from a consideration of the investment involved. For example, a system with 10,000 transformers may represent an investment of one and one-half or two million dollars, and, if underloaded, the unused investment may well approach one-quarter million dollars. At the other extreme, excessive overloading resulting in failures may well cost $15,000 per year for replacement and incidental loss.

MAINTENANCE AND OPERATION

Manufacturers' instructions for the care and operation of transformers cover the storage, handling, and inspection preliminary to installation. They also cover details for drying core and coils, sampling and testing of oil, filling the transformer, and inspection in service. Most important inspection of transformers in service is the periodic check and test of the oil. For large power transformers, such inspection also includes cooling coils and temperature check and should be scheduled for each six months.

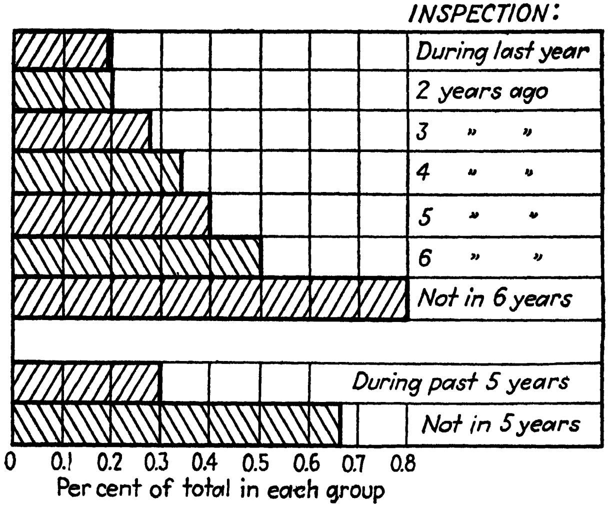


FIG. 67.—Effect of inspection and repair on failures caused by lightning.

For the thousands of smaller distribution transformers, this frequency is not possible or necessary. In fact, because self-cooled transformers require inspection infrequently, they are often checked only when there are specific indications of trouble. Operating records, of the kind shown in Fig. 67, indicate that periodic inspection is of definite value in holding to a minimum the cases of trouble. This inspection includes check of the oil and oil level, locating any indication of oil leakage or siphoning, and inspection and cleaning of the bushings. In addition, a check should be made of the grounding connections, arresters, fusing, and general condition of the installation.

Distribution transformers for general residential service are removed from one location and installed in another, in connection with rearrangements for load increases or due to rebuilding, much more frequently than are large substation and power transformers. It is usual practice to return them to the repair shop, where the core and coil assembly may be removed and cleaned, the bushings and leads checked or renewed, the case thoroughly cleaned and painted, and the oil filtered, before they are given a complete test and placed in stock for reinstallation.

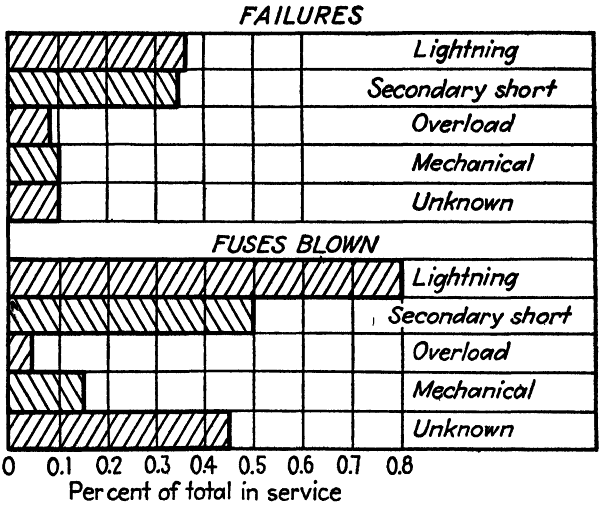


FIG. 68.—Causes of transformer trouble.

Transformer Outages.—It is usually difficult to determine by inspection of a damaged transformer what caused the damage. Two of the major causes of trouble, as outlined in following paragraphs, occur during storms. However, if we are to reduce the cases of transformer failures and of fuses blown, with resulting outages, we must have fairly accurate data on the causes. This necessitates a careful field inspection after each case of trouble.

A summary of transformer troubles and the causes, for an average metropolitan system, is shown in Fig. 68. This is for a period of one year, and the percentage is of the total transformers in service. Failures are counted as all cases where the transformer is removed from service following repeated blowing of fuses. Fuses blown are those cases where a replacement allowed service to be restored and do not include fuses blown by transformer failure, which would result in counting these cases twice. The principal causes of trouble are:

Lightning.—This was formerly the major cause of trouble. Flashover of bushings, terminals, or leads may result in a blown fuse or may necessitate removal of the transformer from service for repair. Surges entering the windings may cause breakdown of the insulation, requiring complete rebuilding of the transformer coils. Protection for this cause is discussed in Chap. XII.

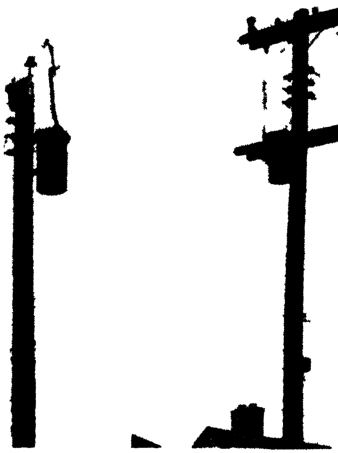


FIG. 69.—Single-phase transformer installations. Left, on rural line. Right, residential area.

Short Circuit.—Overhead secondary lines and services are especially susceptible to this trouble, which causes an overload condition and may finally cause a blown fuse or winding breakdown. Lines through trees are often wrapped together owing to the sway and growth of limbs, and the insulation may be worn off by the rubbing action and a short circuit result. Service entrances sometimes become shorted in conduit or at connections ahead of the service fuses. This subject is discussed more fully in Chap. XI.

Overload.—Even with careful load checks and records, occasional interruptions can be expected from this cause.

Installation.—The majority of distribution transformers, for general residential and commercial service, are installed directly on the line poles For the larger and heavier units, where this is not possible, platforms are built or enclosures are provided on the ground Several typical installations are shown in Figs 69 to 72 In commercial areas, it is common practice to locate the transformers in manholes or vaults under the sidewalk, and in many cases, for both commercial and industrial service, transformers are located in vaults, which are part of the customer's building.

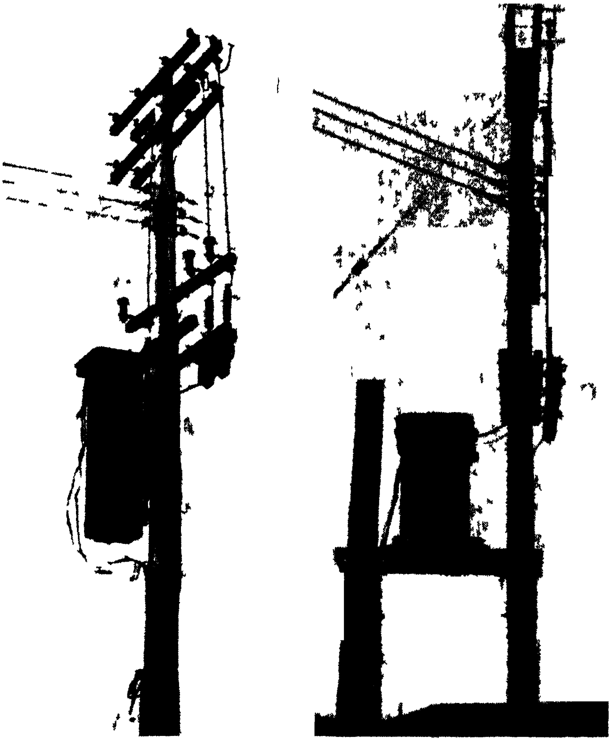


Fig 70—Three-phase transformer installations. Left, mounted on pole Right, mounted on platform.

When installed in buildings, oil-filled transformers must be contained in a fire-resisting enclosure and not directly adjacent to combustible material. Within recent years, a synthetic non-

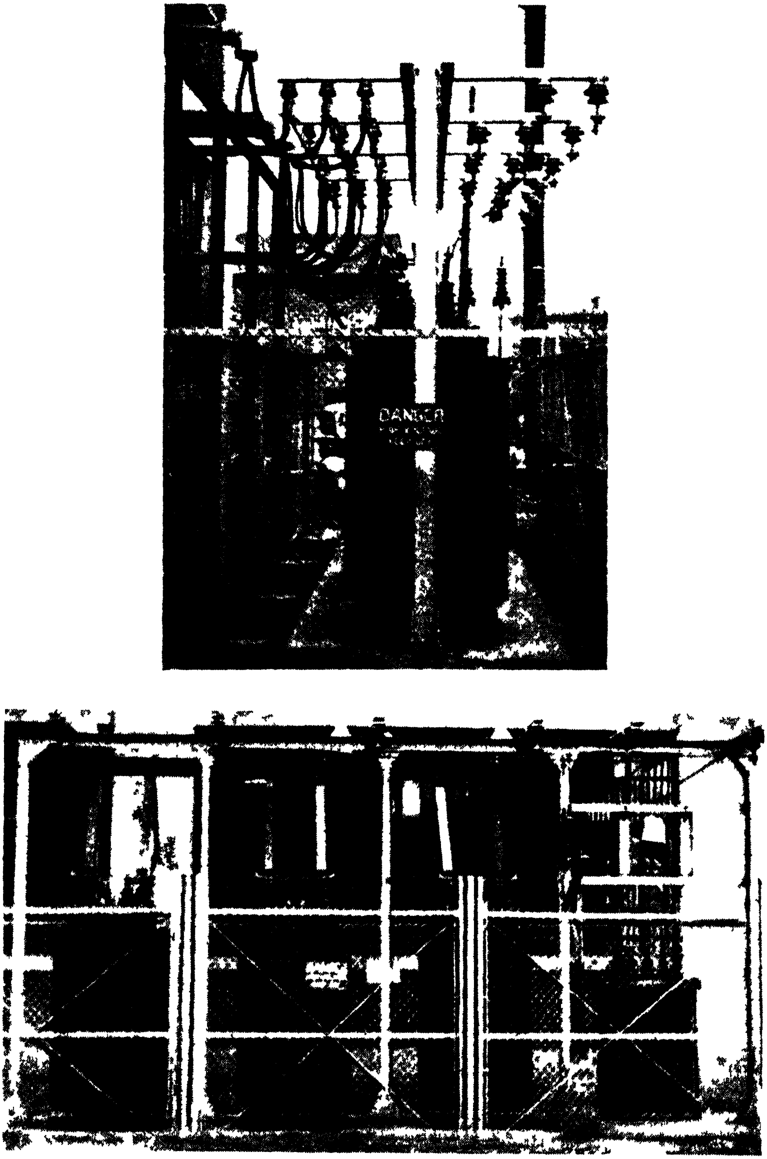


FIG 71.—Large transformer station for factory power and light, end and side views

inflammable liquid has been developed to serve the purpose of oil in transformers. The National Electrical Code permits the indoor installation of transformers using this liquid, without requiring fireproof vaults. For installations indoors or in vaults, either as a part of a building or underground, sufficient ventilation must be provided to carry off the heat of the transformers and to prevent an excessive ambient or surrounding air temperature.

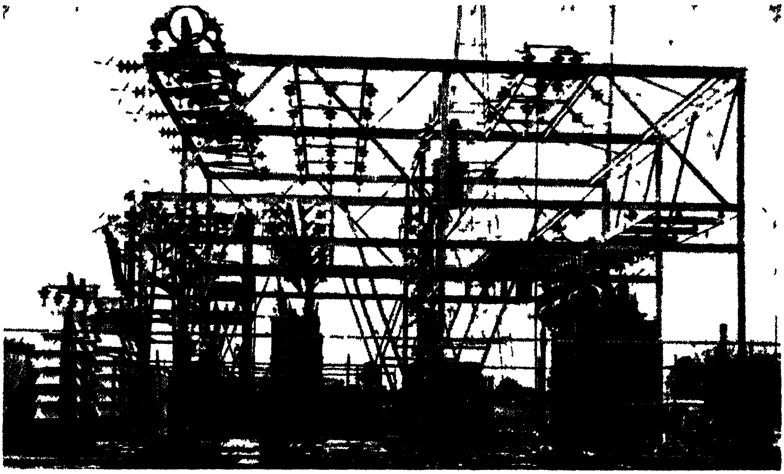


FIG. 72.—Special transformer station with service from two 33,000-volt lines.

TRANSFORMER COMPARISON

Mechanical and general construction of distribution transformers is quite well standardized, at least to the extent of meeting certain specification requirements. Although modifications and improvements are obtainable in various types and makes, they are subject to comparison from the standpoint of operating experiences and judgment, rather than on any direct and definite basis. On the other hand, cost and losses can be definitely compared, and to this end some principles of economics, carefully applied, may bring considerable benefit to the operator.

Economically, the minimum annual cost should be sought, and this includes investment costs and loss costs. No universally adopted figures can be given, but the figures used in the following paragraphs will be illustrative of their application. Variations are due to accounting and operating practice differences, as well as generating costs and load characteristics on various systems. Economic factors are discussed further in Chap. XV.

Under the heading of investment costs are interest on the investment, taxes, depreciation, and operation and maintenance allowance. These charges are applied as a percentage of the cost of the equipment, and, for distribution transformers, values from 11 to 14 per cent are most often used.

Energy consumed in the transformer, due to core loss and copper loss, is lost and must be supplied from the generating station the same as energy that is sold or used. The rate used to determine the cost of this lost energy is usually taken as the minimum cost of supplying energy to that point. On the distribution system, it may be taken as the increment or the fuel cost for energy, not including allowances for operation of the system. If there is a billing meter ahead of the transformer, the minimum block of the rate is used. In the following examples, a rate of ½ cent per kilowatt-hour is used, although for another condition we might use a 3-cent rate, as in the wire size determination problems of Chap. V.

An important value that must be determined is the load condition that is to be applied in finding total copper loss for a year. Transformers to serve an industrial load might have as a basis, 8 hr. per day, 5 days per week, full load, with one-quarter load the remainder of the time. Such an exact load condition would not, of course, be expected, but it may serve as an average. One method of evaluating load for loss calculations is to find the equivalent time of full load that would cause the same total copper loss. This figure, known as *loss factor*, multiplied by the copper loss and the hours in a year gives loss per year. Loss factors for usual load conditions will average between 20 and 40 per cent.

An example will indicate the use of this method to compare two designs of transformer. In this example, we can use an annual investment cost rate of 12 per cent, loss cost at ½ cent per kilowatt-hour, and 30 per cent load loss factor. Design No. 1 of a 5-kva. transformer costs $68.56, and has a copper loss of 105 watts and a core loss of 35 watts. Design No. 2 costs $61.39, with copper loss 110 watts, and core loss 47 watts.

Core loss is continuous, 8,760 hr. per year, and for No. 1 it is

$$8{,}760 \times 35 = 306{,}600 \text{ watt-hours}$$

At ½ cent per kilowatt-hour, cost is $1.53 per year
Copper loss, at 30 per cent loss factor is

$$8{,}760 \times 0.30 \times 105 = 275{,}940 \text{ watt-hours}$$

Cost is $1.38 per year
Annual investment cost of No. 1 is

$$\$68.56 \times 0.12 = \$8.23$$

	Design 1		Design 2	
	Total	Cost per year	Total	Cost per year
Transformer cost	$ 68.56	$ 8.23	$ 61.39	$ 7.37
Copper loss, watts	105	1.38	110	1.45
Core loss, watts	35	1.53	47	2.06
Total annual cost		$11.14		$10.88

SUMMARY AND PROBLEMS

The function of the transformer is to change electric power from one voltage to another. The expansion and growth of electric supply systems have depended upon and followed the development of transformers; and the radius of distribution and transmission has increased as transformers were developed that could operate at successively higher voltages. Transformers can be used only with alternating current, and the economic advantages are so evident that the use of this current has become the accepted system, replacing the original direct current system.

Although the principle and mechanical construction of a transformer appear relatively simple, compared with many other electrical machines and devices, there has been a vast amount of research, invention, and development applied to its parts. Insulation, cooling, core and winding arrangement, and construction details have been improved. Yet many transformers manufactured twenty-five years or more ago are still giving satisfactory service.

In a later chapter, the operation of a distribution system is outlined as being under three separate headings. These three, plus a preliminary, are also included in a complete knowledge of the characteristics of a transformer. As a preliminary, we want to know the voltage ratio and the polarity. For continuity of service, the insulation and the carrying capacity as determined by the temperature rise with load are important. For quality of service, the voltage drop characteristics are required—impedance and regulation. And for cost of operation, the core loss, the copper loss, and the cost of the transformer must be known.

In the operation of a distribution system, whether it be for a large utility or in a small plant, one of the greatest opportunities for use of engineering and economic principles is in the selection and application of transformers to meet the load requirements. Load studies, analysis of characteristics of both transformers and loads, and continued checks are justified to maintain transformer loading on an economical basis.

Problems:

1. One 15-kva. 2,400—120/240-volt one-phase transformer has a core loss of 63 watts and a full-load copper loss of 200 watts. What are its full load and its one-half load efficiency?

2. What size transformer should be installed for a load having 55-kw. demand with 75 per cent P.F., if 100 per cent loading is used? What size would be used if a peak load of 150 per cent of transformer rating can be permitted?

3. A bank of three 500-kva. one-phase 13,200—2,500-volt transformers is to be purchased for an industrial plant load If based on least annual cost, which should be purchased? Use the load condition mentioned as an example for industrial load above (8 hr., 5 days, etc.) with loss cost at ½ cent and investment charge rate of 12 per cent.

Design	*A*	*B*	*C*	*D*
Price each transformer	$1,210	$1,311	$1,153	$1,205
Core loss, watts	1,675	1,850	1,940	1,700
Copper loss, watts	3,775	4,600	3,870	5,100

CHAPTER IX

TRANSFORMER CONNECTIONS

Practically all generation, transmission, and general distribution of electrical energy is with three-phase circuits. We have noted that considerable economy results with three-phase, as compared with one-phase. In Chap. VII, we developed the value $\sqrt{3}$ or 1.73 as a multiplier of volt-amperes to give total power of a three-phase circuit. The voltage is phase to phase (across one pair of wires), and the amperes are in each conductor. This means that with three wires we can obtain nearly one and three-quarter times as much power as we can with two wires. Adding one wire, or 50 per cent, therefore, adds nearly 75 per cent to the power And, of course, one additional wire does not add anywhere near 50 per cent to the cost of a line, when all costs of construction and installation are considered.

Services to customers' wiring may be either one-phase or three-phase. Single-phase is used for lighting and small appliances and is the basic supply in residential and outlying commercial areas. Three-phase service is used for industrial and large power loads and often also for combination power and lighting service in the larger commercial areas (see Fig. 22).

Connection of a one-phase transformer to two wires is a simple matter, but connection of three one-phase transformers to a three-phase circuit requires use of certain fundamental principles that must be kept well fixed in mind to avoid trouble. And when two three-phase banks are to be connected in parallel, or other special connections are to be made, a clear understanding of these basic principles is very essential. It is our purpose in this chapter to consider these principles and fundamentals. There are many special connections for special service or for interconnection of two power systems, etc., that will not be covered here.

Single-phase Connections.—Standard distribution transformers have their secondary windings in two sections. For example, a 2.400—120/240-volt transformer, with four secondary leads, and be connected as shown in *a*, *b*, or *c* of Fig. 73. Connection with the two coil sections in parallel, as shown in *a* to give 120 volts, is not used so commonly as the connections for three-wire service, 120 or 240 volts, shown in *b*. Connections *a* or *c* to give 120 volts or 240 volts would give 240 volts or 480 volts in the

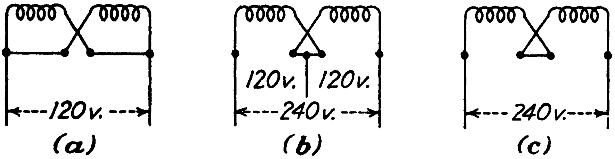


Fig. 73.—Single-phase transformer connections.

case of a transformer with secondary rating 240/480 volts. These connections are most frequently used for the individual units of a three-phase bank.

Secondary circuits that supply interior wiring systems must, in the interest of safety, have one point grounded, as outlined in the National Electrical Code. The principles of grounding are discussed in Chap. XII. It is common practice to ground the

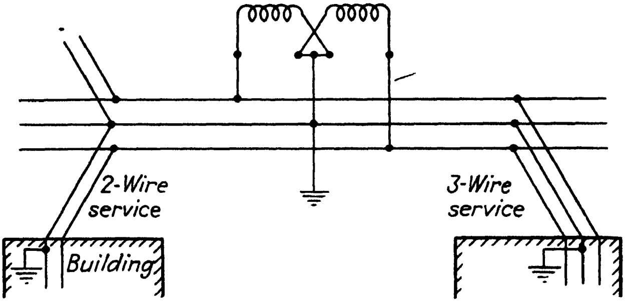


Fig. 74.—Three-wire secondary with mid-point grounding.

mid-point of the secondary winding at the transformer and at all service entrances, as shown in Fig. 74. This arrangement is used for the secondary main and services outlined in Fig. 20, Chap. III.

THREE-PHASE CONNECTIONS

For three-phase service, there are two transformer connections commonly used; (1) delta and (2) star (also referred to as Y or Wye). Three combinations of these two connections are commonly used; (1) delta-delta, (2) delta-star, and (3) star-delta.

Delta connections are made by connecting adjacent terminals or leads of the three transformers, as shown in Fig. 75. The end lead of one winding is connected to the beginning lead of the next winding and so on to the end of the third transformer winding, which is connected to the beginning lead of the first transformer. With this connection, each winding has the same voltage as the phase to phase voltage of the line to which it is connected.

Star connections are made by connecting the similar leads together, as shown in Fig. 76. With this connection, each winding has the voltage of phase to neutral of the line to which it is connected, or the phase to phase voltage divided by $\sqrt{3}$. Thus, three 2,400-volt transformers are connected star to a 4,160-volt line. A neutral connection may be made to the neutral point, or it may be omitted

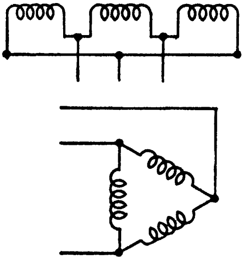


FIG. 75.—Delta connection

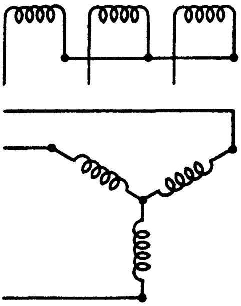


FIG 76.—Star (or Y) connection.

Analysis of Connections.—An analysis of the construction of voltage or vector diagrams may be the best approach to an understanding of the fundamentals of transformer connections. Such analysis may not be necessary when a single transformer bank is connected to serve a load, but, even then, it is essential that we understand the principle of the connection.

The relative phase rotation, as shown by the analysis, is most important when two or more banks are to be connected in parallel. This is the case whenever we have two circuits that may at times be tied together, two banks operating in parallel to obtain required capacity, or while load is being transferred from one to another, or when several banks supply a network.

We have considered the use of vectors to illustrate relative time characteristics (page 80), and Figs. 42 and 43 show three of the possible relative positions. We can assume any one of these diagrams to determine the relation of the primary and secondary. In Chap. IV, we noted that three generator coils or loops rotate together and that the voltage and current values hold a definite relative time position. Voltage reaches a maximum in one direction on one phase and starts to decline; then it reaches a maximum on another phase, and then on a third. For convenience, the phases are indicated as *A*, *B*, *C*, or 1, 2, 3. Phase rotation may then be *A*-*B*-*C* or *A*-*C*-*B*. Our interest in this rotation, in transformer connections, is to know the *relative* rotation on the secondary side of the bank compared with the primary.

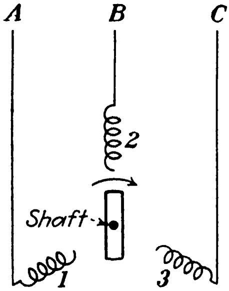


Fig. 77.

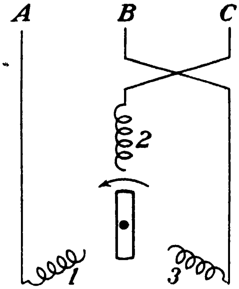


Fig. 78.

Three-phase motor reversal by reversing two supply leads.

Motor Rotation.—Our discussion of relative rotation in transformer connections may be assisted by an explanation of motor rotation and reversal. Figure 77 shows a simple diagram of a three-phase motor. When the voltage of the supply circuit phase *A* becomes maximum, motor coil 1 is energized, drawing the magnet on the motor shaft toward it. A fraction of a cycle later, the voltage of supply circuit phase *B* is maximum, and phase *A* is declining. Coil 2 of the motor then exerts a stronger pull than coil 1, and the magnet will be turned in the direction of 2. A fraction of a cycle later, in the same way, the magnet is attracted toward coil 3.

Now, if we *reverse any two* of the leads, for example *B* and *C*, so that phase *B* is connected to coil 3 and *C* to 2, as in Fig. 78, we reverse the direction of motor rotation. Instead of being drawn clockwise, in the diagram, from coil 1 to 2 to 3, the magnet will now be drawn counterclockwise from coil 1 to 3 to 2. In this explanation, we have considered only the voltage in one direction. Actually, of course, the part of the voltage wave in the opposite direction also acts in the motor.

Standards for designating transformer terminal leads and phase notations are related to the direction of rotation, as might be indicated by a motor. If a three-phase motor should be transferred from the high-voltage circuit to the low-voltage side, thus transferring each terminal to its corresponding terminal, *A* to 1, *B* to 2, and *C* to 3, the direction of motor rotation would be the same.

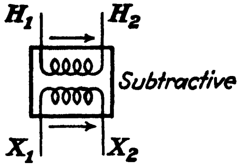


Fig. 79.—Subtractive.

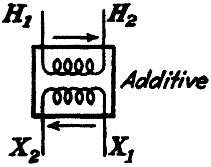


Fig. 80.—Additive.

Lead or terminal marking and relative voltage directions are determined by transformer polarity.

Polarity of the three transformers is of the utmost importance in making three-phase connections, since the relative directions of the voltages and currents in the transformers are dependent on the order in which the terminals are connected to the windings. In analyzing connections, the first step is to show the relative directions on a connection diagram. These directions refer to the leads outside the case.

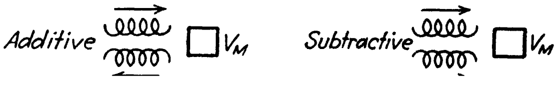


Fig. 81.—Simplified diagram of polarity.

In Fig. 79, the arrows are shown for a subtractive polarity transformer. The leads are marked so that at the instant current is flowing in on lead H_1 and out on lead H_2, it will also be flowing in on lead X_1 and out on lead X_2. The relative directions of the arrows for this *subtractive* connection should be noted—in the *same* direction.

In Fig. 80 for an *additive* polarity transformer, the relative directions are *opposite*, as shown by the arrows. The H_1 and X_1 leads are now diagonally opposite on the case, to maintain the same relative direction of flow—H_1 to H_2 corresponding to X_1 to X_2.

Referring to the polarity test connections, shown in Fig. 58, may help at this point. In additive polarity transformers, the test voltage across adjacent primary and secondary leads is greater than the voltage impressed on the primary winding. The voltages of the two windings add together across the leads to which the voltmeter is connected. In subtractive polarity transformers, the test voltage is less than the impressed voltage, or the voltages of the two windings are opposing or subtracting in the voltmeter connection. This point must be remembered, and it is repeated, in simplified form, in Fig. 81.

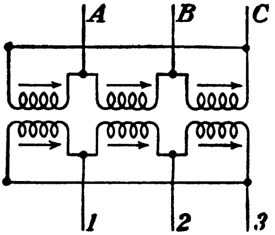


Fig. 82.—Delta-delta connected bank of subtractive polarity transformers.

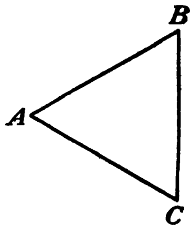


Fig. 83.—Primary vector diagram for the transformers of Fig. 82.

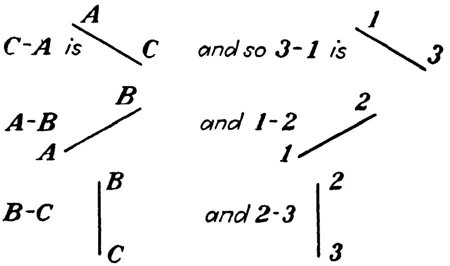


Fig. 84.—Step-by-step method of determining secondary vectors.

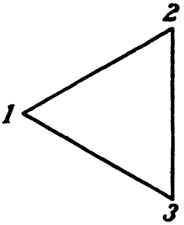


Fig. 85.—Secondary vector diagram for the transformers of Fig. 82.

In checking or analyzing the connections, the first step is to show the relative directions on a connection diagram. The leads are lettered or numbered on one side, usually the primary, according to the line, if known, or the notation is assumed if not known. Three bank connections are analyzed here to illustrate the method. Although the steps are simple, care must be used to avoid errors.

Delta-delta connected, subtractive polarity transformers are shown in Fig. 82. The primary line is marked *A-B-C*. We first indicate the relative directions with arrows pointing in the same direction (subtractive). The primary arrow, as shown in the figure, points to phase *A*. The secondary arrow points to phase 1. In the next transformer, the primary arrow points to *B*, and we designate the lead of the corresponding secondary as 2. Secondary 3 corresponds to primary *C*. The secondary line could also be marked *a*, *b*, *c*, or by other designation.

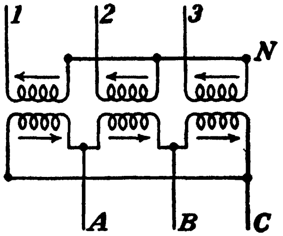


FIG. 86.—Star-delta connected bank of additive polarity transformers.

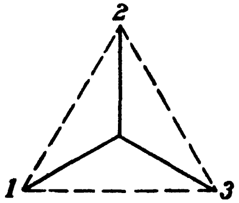


FIG. 87.—Primary vector diagram.

We now show the vector diagram for the primary, known for the line or assumed for our purpose of determining the relative diagram for the secondary, as in Fig. 83. Next we show each secondary vector, corresponding to the parallel primary vector. This is done step by step, as in Fig. 84.

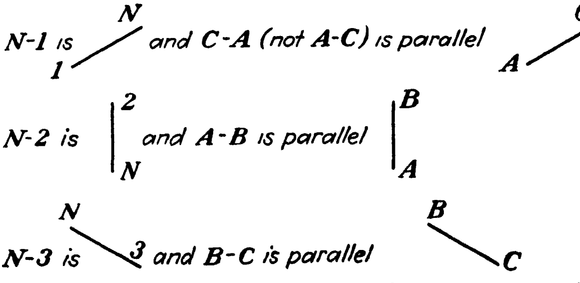


FIG. 88.—Secondary vectors determined step-by-step.

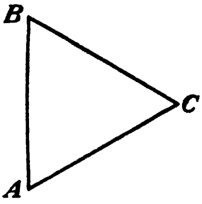


FIG. 89.—Secondary vector diagram.

We can then join the three secondary vectors together, as in Fig. 85. This is, then, the secondary diagram, corresponding to the primary diagram of Fig. 83, for this bank connection.

Star-delta connected, additive polarity transformers are shown in Fig. 86. The primary line is marked 1-2-3. We indicate the relative directions, with arrows pointing from the neutral in the star connection, and in the opposite direction (additive) in the secondary. Next, the secondary leads are marked *A*-*B*-*C*; using *A* to correspond to 1, etc., and being sure to follow the arrows and note *A* as the lead diagonally across the transformer, and not adjacent or directly opposite.

We assume a primary vector diagram as in Fig. 87. Note that the transformer winding voltages are indicated by the star, with solid lines, and the phase to phase voltages may be shown by the dash line. The secondary vectors correspond to the primary *winding* vector, as shown in Fig. 88. The three secondary vectors are then joined, as in Fig. 89.

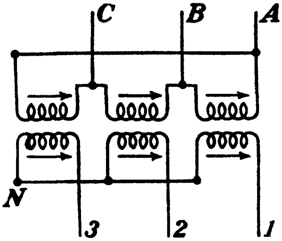


FIG. 90.—Delta-star connected bank of subtractive polarity transformers.

Delta-star connected, subtractive polarity transformers are shown in Fig. 90, with primary vector diagram as in Fig. 91. In the secondary

N-1 is in direction *B*-*A*
N-2 is in direction *C*-*B*
N-3 is in direction *A*-*C*

The three secondary vectors are joined, as in Fig. 92.

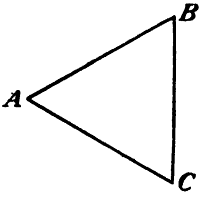


FIG. 91.—Primary vector diagram.

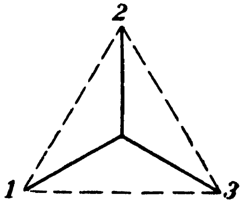


FIG. 92.—Secondary vector diagram.

Reversal in the primary connections gives a displacement in the secondary diagram. Figure 93 is the same as Fig. 90, except that two primary leads are reversed, to the order *B*-*C*-*A* instead of *C*-*B*-*A*. With the same primary vector diagram (Fig. 91)

N-1 is now in direction *C*-*A*
N-2 is now in direction *A*-*B*
N-3 is now in direction *B*-*C*

We now get a secondary diagram as in Fig. 94, which is the same as Fig. 92 except that it is rotated 60 degrees in a clockwise direction.

Reversal of the neutral connection on the secondary, as in Fig. 95, which has the same primary connections as Fig. 90, gives the same displacement as reversal of two of the primary leads. The secondary diagram is again as shown in Fig. 94.

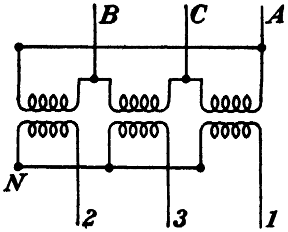


FIG. 93.- Same bank as shown in Fig. 90, but with two primary leads reversed.

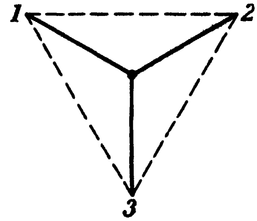


FIG. 94.—Secondary vector diagram with connection of Fig. 93. (Compare with Fig. 92.)

Open-delta connections are often used for emergency operation in case of failure of one transformer in a bank. This connection may also be used to postpone investment, by omitting the third transformer of a bank until the full capacity is required. Still another common application is for a three-phase power service, when a phase and neutral line is serving the area and a second phase wire can be added, but the third phase wire is not necessary.

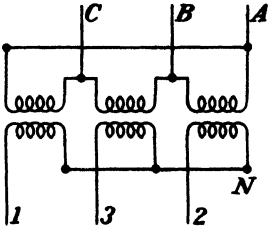


FIG. 95.—Same bank as shown in Fig. 90, but with neutral connection reversed.

Open-delta connections are made in the same manner as standard delta, with one transformer omitted. In the case of a delta-delta bank, in which one transformer is to be cut out of service, the leads of this transformer are simply disconnected and no other changes made, Fig. 96. A common error is to try making other changes in the connections of the two remaining transformers.

In the case of a star-delta bank served from a four-wire line, the neutral of the line is not ordinarily connected to the neutral of the transformer connections. When one transformer is cut out of service, or omitted, the line neutral and the bank neutral must be connected, as in Fig. 97. Open-delta connections cannot be made from the delta-star connections.

The open-delta connection has some inherent disadvantages, one of which is that the capacity is reduced to 58 per cent of the rating of the closed delta bank, instead of two-thirds, as might be expected. The bank capacity is still further reduced if the load is not balanced or symmetrical on the three phases, which may result if some single-phase load is connected to the three-phase service.

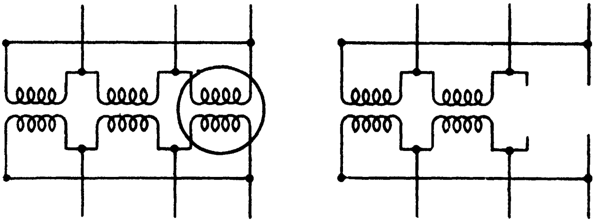


FIG. 96.—Delta-delta connected bank changed to open-delta by disconnecting leads of one transformer

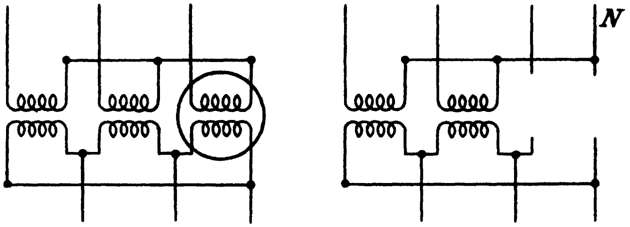


FIG. 97.—Star-delta bank to open-delta. Neutral bus of bank must be connected to primary neutral.

Standard connections are usually adopted for individual electric systems to meet the conditions and practices for that system. These may or may not correspond to the examples shown here. The important point for our purpose is to follow the steps by which any combination can be analyzed, and connections can be arranged to arrive at a desired diagram.

The relative position of the primary and secondary voltage diagrams is referred to as *angular displacement*. In Figs. 83 and 85, the angular displacement is 0 degrees. If, however, the secondary is connected so that the diagram is in a relative position similar to the diagram of Fig. 89, it would be referred to as displaced 180 degrees, relative to the primary. This displacement would result also if the transformers connected as in Fig. 82 are additive instead of subtractive. This can be checked by the reader, for practice in analyzing the connections.

In Figs. 87 and 89, the angular displacement is 30 degrees. This is true of all delta-star and star-delta combinations.

Mid-point taps in the secondary windings, as shown in Fig. 98, are used for protective purposes, as discussed in a later section on grounding, Chap. XII. The connection is commonly made at the secondary bus of the transformer installation, and the fourth wire is not carried into the interior wiring. This tap may also be used for lighting service, with 120 volts between the phase wire and the ground wire. It is ordinarily not so satisfactory for this purpose, however, as a separate transformer for lighting service.

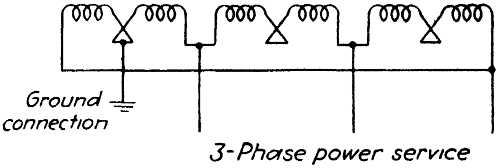


FIG. 98 — Mid-point tap grounding of delta-connected secondary

Three-phase Transformers.—In the past, nearly all three-phase installations were made with three one-phase transformers. There has been a steady increase in the use of three-phase units, however, because of the smaller space requirements and the savings in installation cost. They are essentially three separate transformers, built together in one bank and with connections between coils made inside. Bus and outside wiring connections are thus reduced to a minimum.

Using three one-phase transformers has the advantage that in case of a winding failure, one transformer can be cut out of service and later replaced and temporary service given with two transformers in open-delta. Owing to the relatively infrequent failures of large transformers, this advantage may be of slight importance. Portable units for temporary service or a temporary tie to an adjacent secondary main are possibilities for the smaller three-phase services, in case of a transformer failure.

Special Connections.—There are a number of other connections that are used for special services and for phase transformation or displacement for interconnection between two systems with unlike phase arrangements. These include the Scott, Taylor, and Fortescue connections for three-phase to two-phase, and the diametrical, double-delta, or double-star connections for three-phase to six-phase.

Autotransformers are often used for special applications and may effect savings, when compared with standard transformers, especially in the higher voltage ratings. One winding only is used and a tap brought out of this winding, so that the desired voltage ratio is obtained as the ratio of the total winding to the section to the tapped point.

Star-star connections must be used with caution because of the possibility of distorted voltages. It is practically impossible to obtain three transformers with exactly the same magnetizing current, and a very slight unbalance in the secondary load will result in a large voltage shift of the neutral. This result is in contrast with connection combinations in which one is delta. In this case, the unbalance in magnetizing current is adjusted by circulation among the transformers, through the delta connection.

These connections can be used if (1) a third winding in each transformer can be connected in delta (tertiary winding), (2) the neutral of either the primary or secondary side can be connected to the neutral of a star-delta connected bank, or (3) the primary neutral can be carried back to the source of power.

PARALLELING TRANSFORMERS

An analysis of connections will usually save labor in paralleling, particularly when the primaries are from different or removed sources. When two banks of transformers are supplied from the same primary or from adjacent primary lines that can be paralleled, a *paralleling test* will ordinarily suffice. In any case, even if all connections appear clear and simple, the lines to be paralleled should always be tested before they are tied together. Omission of the test may bring disastrous results, since there are a multitude of possible combinations in the connections to be paralleled, only a few of which are correct.

A very important use of paralleling is in cutting a new transformer bank into service, to change capacity or for replacement, without interrupting service. Synchronizing equipment, for paralleling lines, is used in substations supplied from separate power sources, but a voltmeter is all that is necessary on the distribution system, and the method is fairly simple. In Fig. 99, the two 240-volt three-phase secondaries are to be paralleled. The test method follows:

1. Check the voltages of all phases of both banks. *E ab, bc, ca* and *E 12, 23, 31* must be approximately equal.

2. Check for voltage between one bank and the other. There should be no voltage (*a1*, *a2*, *a3*, *b1*, etc.) with the leads not

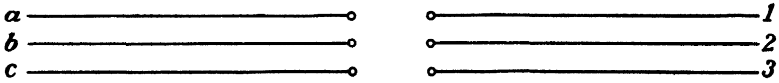


FIG. 99.—Two three-phase lines to be paralleled.

connected. A voltage reading would indicate a ground or other connection.

3. Connect one wire of first bank to any wire of second bank. Test between remaining wires. For example, tie *a* to *1* with temporary lead. Test *b* to *2*, *b* to *3*, *c* to *2*, and *c* to *3*.

4. If voltages read in (3) *are zero* between two pairs of wires, parallel can be made between these two pairs and the temporary connection tied in.

5. If voltages in (3) are *not zero*, try the temporary connection between another pair as *a* to *2*. Again test for voltage as in (3). A third attempt may be necessary, *a* to *3*.

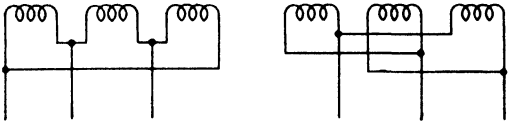


FIG. 100.—Reversal of delta connection.

6. If no combination is found in these three trials, in which voltages are zero, a parallel is not possible with the two secondaries. It is then necessary to reverse the rotation of the secondary *of one bank*. This can be done in any one of three ways:

a. Reverse any two wires of primary line connection to one bank, as Fig. 93 compared with Fig. 90.

b. For star connection, interchange phase and neutral lead of each transformer. Leave each transformer connected to same phase of line as before.

c. For delta connection, interchange the two leads of each transformer. Leave each line lead connected to same two transformers as before (Fig. 100).

Parallel Operation.—It is sometimes expedient to operate two transformers in parallel, to increase the service capacity. The paralleling tests are the same, in cutting the two banks into service, and there are two other factors that must be given consideration to ensure proper operation.

The secondary voltages of the two banks must be approximately equal (step 1 above) to parallel. However, for continued parallel operation they should be exactly equal. A slight difference in voltage ratios will result in the establishment of circulating currents in the windings. The effect of circulating current is to add to the load current in the transformer having high induced voltage and to subtract from the load current in the transformer having low induced voltage.

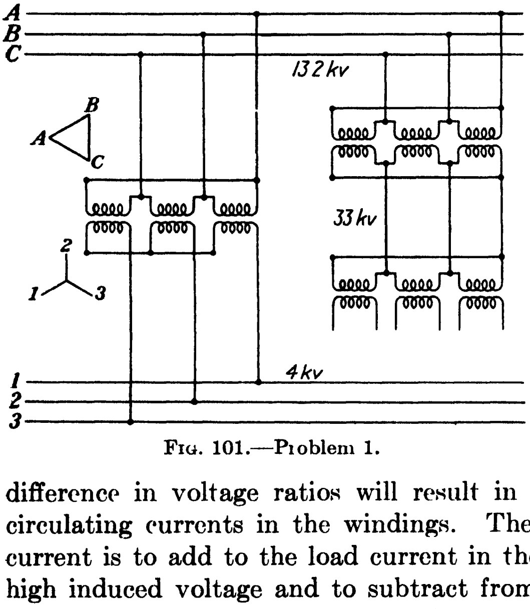


FIG. 101.—Problem 1.

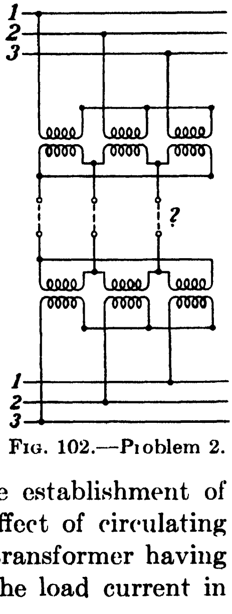


FIG. 102.—Problem 2.

Impedance of the transformers also affects the division of load between them. There may be enough difference in impedance to overload one of the transformers, and it is necessary to check this by calculation or by a test of current with the banks in parallel operation.

SUMMARY PROBLEMS

1. Completing the connections for the 33—4-kv bank of Fig. 101 so that it can be paralleled with the 13.2—4-kv. bank will, perhaps, offer the best summary of this chapter. The 13.2—33-kv. bank has additive polarity (not standard), and the 13.2—4- and 33—4-kv. banks have subtractive polarity (standard). The reader should draw in the 4-kv. connections. (Refer to Appendix for correct connections.)

2. The transformers of Fig. 102 are additive polarity. Will the two banks operate in parallel with connections as shown? If not, what change is necessary so that they can be paralleled?

3. Suppose that a motor runs in the same direction when connected to two different services. Does that prove that the services can be tied together to parallel?

4. Prove by vector diagram that the open-delta connection gives the same voltage as its corresponding delta connection. Does cutting out one transformer of a bank cause reversal of the secondary rotation?

CHAPTER X

VOLTAGE CONTROL

All lamps, appliances, and apparatus that use electrical energy for their operation are designed for a certain operating voltage. Variations are permissible but are limited to a certain range above and below the rating for satisfactory operation. It is essential that the distribution system maintain voltage within these limits. Since all supply lines and equipment for distribution cause some drop in voltage as current flows through the resistance and reactance of the circuit, the amount of drop, and its variation with load, is important.

This problem of voltage control is the main controlling factor in the design of practically all distribution circuits, whether they be for major transmission, urban distribution, or rural extension. Although current that may cause excessive heating is the first consideration in interior wiring design and in equipment and apparatus ratings, voltage drop is also of primary importance in the design and selection of rating or size.

Voltage control may be considered under two general headings:

1. Design of the circuits to hold the voltage variation within the limits, changing conductor size or other design factors to reduce the voltage regulation inherent in the circuits. This was discussed in Chaps. V, VI, and VII.

2. Regulation of the voltage supplied to the circuit, adding voltage to overcome the drop in the lines, either on the supply side or on the load side, or both, of the regulating point. Regulation may be either a fixed amount or variable, as considered in the following paragraphs.

Voltage variations also fall under two general headings:

1. Changes that are slow and of a relatively steady nature, due to changes in the load. Without regulation or control, the voltage during the low load period may be high, and at the time of maximum load it may be low. Both the design of circuits and the regulating of voltage supply affect the variations of this type.

2. Changes that occur suddenly and momentarily, due to sudden load changes. Motor starting currents are the principal causes of these sudden changes. Lamp flicker due to this fluctuation may be sufficient to be annoying, and regulation of the supply does not help because the variations are so rapid that the usual regulating equipment cannot adjust for them.

Limits of variation that are permissible for satisfactory operation vary considerably. Lamps are the most critical of common devices, both in steady variations and in fluctuations. Heating appliances are not affected by fluctuations and are not so critical of variations, but slow operation will result from voltage greatly below their rating. Motors operate satisfactorily with voltage 10 per cent above or below their rating. Low voltage causes dim lights, but high voltage shortens the life of lamps, and excessively high voltage will cause failure of appliances, as well as of lamps.

Test data for incandescent lamps show a 7 per cent reduction in watts and an 8 per cent reduction in efficiency, with 5 per cent below normal voltage, and correspondingly higher wattage and efficiency for 5 per cent above normal voltage. There is a 53 per cent decrease in life for a 5 per cent increase in voltage above the lamp rating, with a 90 per cent increase in life for a voltage 5 per cent below rating. Of practical importance in the effect on lamp life is the fact that lower voltage accompanies maximum load, so that lamp life is not shortened greatly, unless the lamps are in operation also through the low load period.

It is not possible, of course, to maintain exactly rated voltage at every lamp. Limits of tolerance in variation may be from 2½ to 5 per cent above or below standard. A practical value as a measure of good service in high load density areas may be 3 per cent, although this limit may not be practical or economical on a low load density rural line.

Both for customer service satisfaction and for economic operation, voltage within fairly close limits is essential where lighting is being supplied. For this reason, it is usual practice to install regulating equipment on feeders in residential and commercial areas, although this is not ordinarily necessary for circuits supplying power loads. Regulating equipment and changes in lines can definitely be justified on an economic basis, by the increase in energy use, if the voltage is low during load periods.

FLUCTUATING VOLTAGE

Limits of voltage fluctuation, in contrast with the steady variations from normal, cannot be set up on so definite a basis. They depend on visual perception, lamp design, and individual expectancy or annoyance. An occasionally flickering light may not cause annoyance, but if it is periodic and continued it may be very annoying. Thus, there are two factors: the amount of voltage fluctuation and also its frequency of occurrence.

Fluctuation or flicker is of two types, depending on its frequency of occurrence:

1. *Noncyclic* flicker is that corresponding to occasional voltage fluctuation, such as may be caused by the starting of a motor. This problem was first widely noted with the use of refrigerators and has been further increased by the introduction of stokers, blowers, and other large motor equipment in the home. In stores and commercial buildings, it is commonly associated with elevator motors. Starting of large industrial motors may cause fluctuation to many or all other services on the same line.

2. *Cyclic* flicker is a repeated change that may be encountered with pulsating loads, such as compressors of the reciprocating type. This has been a problem accompanying air conditioning, which is often on the same interior circuits or services with lighting load.

Load growth in recent years is closely associated with increased use of household and commercial appliances. Motor driven appliances, connected to the same wiring and service lines with lamps, have greatly increased the possibility of voltage fluctuation. The result has been an increase in light flicker. At the same time, greater attention has been focused on quality of lighting, and the result has been an increase in expectation for absence of flicker. These two trends have led to a number of investigations to determine the limits of tolerance of flicker.

The results and conclusions of these investigations are important in the design of motor operated appliances, in the layout of interior wiring, and in the design of lighting. Different types of lamps have different characteristics, because of the difference in time constants, or ability to retain incandescence during the drop in voltage. It has also been found that with higher levels of general illumination the effects of fluctuation are less noticeable or annoying than with an individual lamp or illumination at lower levels.

Figure 103 shows the results of one series of tests to determine objectionable fluctuation. The limits were averaged from a group of observations. Continued or cyclic flicker was found to be most severe when its frequency is between 4 and 10 per second. At this frequency, which may occur with reciprocating compressors, one-half volt variation may cause annoying flicker, and if the frequency is increased to 28 per second, the allowable variation is 2.4 per cent, or about 3 volts.

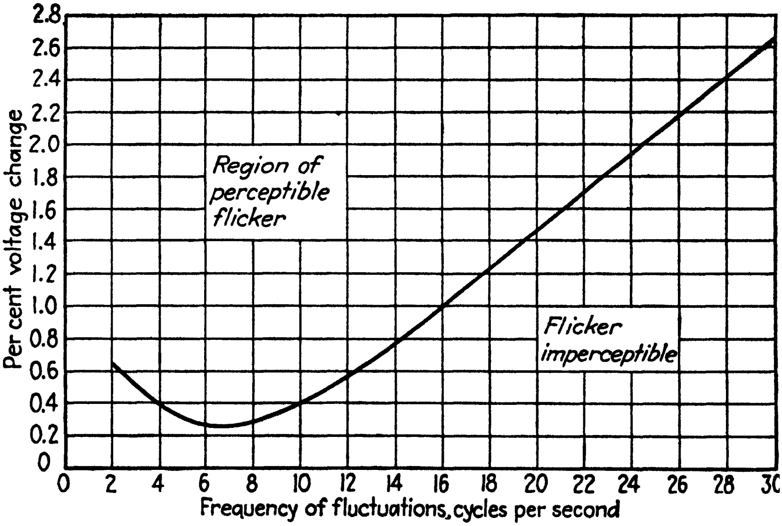


FIG. 103.—Annoyance of voltage fluctuation depends on its frequency.

It has been observed that, within limits, the slower the rate of change, the greater the total voltage change necessary before flicker is noticed. A drop of 3 volts may be no more noticeable, if it takes one second, than an abrupt drop of 2 volts. A limit of 2 volts appears to be a fair design criterion for allowable fluctuation, if the occurrence is frequent or periodic. With less frequent variations, the drop may be as much as 5 volts. The time of the variation is also important; there may be greater variations during the day than during the evening periods.

Data of this nature are essential in determining service requirements and motor starting currents and also for supply to air conditioning equipment. Electric supply systems must have some limitations on permissible starting currents and abrupt loads, such as welding equipment, where such equipment is supplied by residential area feeders. This is especially true for small industrial plants, although larger plants may be supplied by feeders for industrial load only and not be so subject to these limitations.

Starting currents of motors are several times their full-load running currents. Current limiting starters can be applied to reduce the amount, or increments, of drop during the starting period. Motors can also be designed to start with lower currents than normally required, and their use often will make the starting equipment unnecessary. Motors of less than one horsepower offer a special problem, because they are more common in residential use. A common limitation, for example, is 20 amperes starting current for a ½-hp. motor for 120-volt service. Motors on three-phase service often have limitations for starting current not to exceed three to four times the full-load rating.

METHODS OF REGULATION

Regulation of voltage on a supply system must be closely correlated with the design of lines. Although the design is of primary importance in control of voltage fluctuations, the regulation of supply voltage is of equal importance in maintaining the voltage at a normal level. This regulation, on a small system, may be at the generators, but on a large supply system it is usually necessary to control individual substations, or feeders, or nearer the loads.

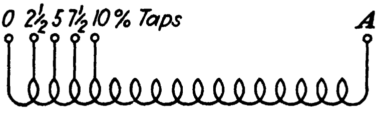


FIG. 104.—Taps in transformer windings.

Fixed control is provided by transformer taps, booster transformers, or by reducing the drop by reduction of the current for a given load. Often, this type of control is sufficient during an initial load condition, and as the load increases, automatic regulation may be added. With fixed control, the voltage is raised a certain amount, and this is not varied as the load changes.

Automatic control is most commonly provided by induction-type voltage regulators. More recent developments include switching arrangements for changing taps or cutting a fixed amount of boost in or out of the line. The selection of method will depend on individual conditions and cost, as well as the results required.

Transformer taps (Fig. 104) provide the most economical means of raising voltage to offset voltage drop either ahead of or beyond the transformer. With the general arrangement of taps outlined in the chapter on transformers (page 104), it is possible to raise the secondary voltage above the secondary rating or to deliver rated secondary voltage with less than rated primary voltage. They are most useful for individual power services but are less commonly used for general secondary services, where primary feeder regulation or control can be used instead of the taps in a large number of transformers.

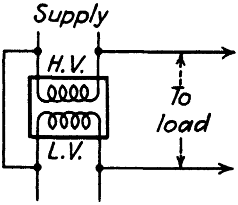


FIG. 105.—Boost.

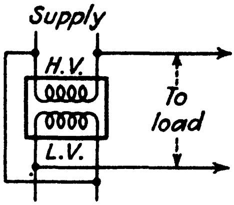


FIG. 106.—Buck.

Connections to raise or lower voltage (with an additive polarity transformer)

Booster connections can be made with standard transformers, based on the principle of the polarity tests outlined in Chap. VIII, (page 105). Figure 105 shows the connections for boost, with an additive polarity transformer. The supply voltage connection is the same as in the test, with adjacent primary and secondary leads tied together. Load connections then correspond to the test voltage reading, from the free secondary and primary leads. Figure 106 shows the connections for reducing or "bucking" the voltage with an additive polarity transformer. With subtractive polarity, these two are reversed, Fig. 105 giving *buck* and Fig. 106, *boost.*

The percentage of voltage change with the booster connection depends on the ratio of the primary and secondary windings of the transformer, the secondary voltage being added to, or subtracted from, the primary voltage. For example, with a 2,400—120/240-volt transformer, using the 240-volt secondary, the ratio is 10 to 1 and the secondary is 10 per cent of the primary. With the 120-volt secondary, the ratio is 20 to 1, and the secondary is 5 per cent of the primary.

With this connection, the load current must pass through the secondary winding, and the size of the transformer required is: kilovolt-amperes of the load times percentage of boost. *For example,* the voltage to a 50-kva. load is to be raised 10 per cent

10 per cent of 50 kva. = 5-kva. booster

These connections are not recommended for extensive use on distribution systems, because the secondary winding insulation is stressed by the primary voltage. There are times when such an installation is the only economical solution for a voltage control problem or when a temporary connection is necessary until a permanent rearrangement can be made. The principle of the connection is important for our consideration of regulators.

Automatic tap changers and boosters are available to make more advantageous use of these two arrangements. The objection to fixed boost is that, during low load periods, the voltage supplied may be higher than desirable. Automatic switching, controlled by a voltage relay to cut the boost in or out or to change from one tap setting to another, overcomes this objection. Automatic voltage boosters are less expensive than induction regulators and are important additions to equipment available for improving service in low load density areas, particularly on long rural lines.

Automatic tap changing under load is also used with larger distribution transformers and power transformers in substations to control voltage on a bus or feeder. An important application is to control power flow in an interconnection between parts of the system by varying the voltage of the interconnecting line.

An important principle in these automatic switching arrangements for booster or tap changers is that the circuit must not be opened while the transfer is being made from one position to the next. One arrangement uses two adjuster arms which are normally in parallel. When one arm is moving from tap to tap, the other arm carries the load.

Induction Regulators.—In the metropolitan and suburban areas served by major substations, the most common form of voltage control for distribution feeders is by means of induction voltage regulators at the substation. With their auxiliary equipment, they provide the best and smoothest control available.

The principle of the regulator is similar to that of the standard transformers, with connections similar to those of the booster.

In the booster connections, a change from boost to buck is made by reversing either the primary or secondary connections. As it is the relative direction of the two windings that determines the effect, the same change could also be made by reversing either the primary or secondary winding. With reference to the elementary transformer design, the booster connection could be shown as in Fig. 107.

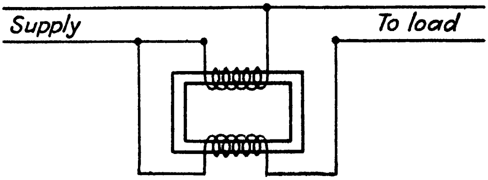


FIG. 107.—Elementary diagram of transformer connected for boosting voltage.

A section of the core could be cut on each side of one winding. With this section mounted on a shaft, a reversal of the winding could be accomplished by rotating the shaft through one-half revolution, Fig. 108. The windings and core are, of course, arranged to give better and more efficient operation than this elementary form. The position of the shaft and movable winding determines the amount of voltage increase and decrease between the two limits of extreme boost and buck.

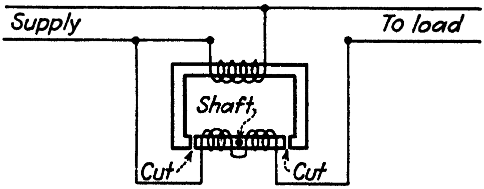


FIG. 108.—Section of core cut and mounted so that it can be turned. Elementary form of induction regulator.

Auxiliary switches and relays control the motor operation, and the "brains" of this control are the contact-making voltmeter and the line-drop compensator. The compensator is a miniature feeder line. As shown in Fig. 109, current from a current transformer in the line, passing through the equivalent resistance and inductance, produces a drop in voltage proportional to drop in the line.

This drop is subtracted from the voltage of the potential transformer to give a voltage that is proportional to that at a point on the line corresponding to the compensator settings. The resulting voltage operates a voltmeter, which has contacts with connections to a reversing switch. When voltage is higher than the setting, the voltmeter arm swings upward to a corresponding contact and closes the circuit to one side of the switch. This causes the motor to turn the regulator in the direction to lower voltage. If voltage is lower than the setting, the opposite contact and side of the switch are used to cause the regulator to raise voltage.

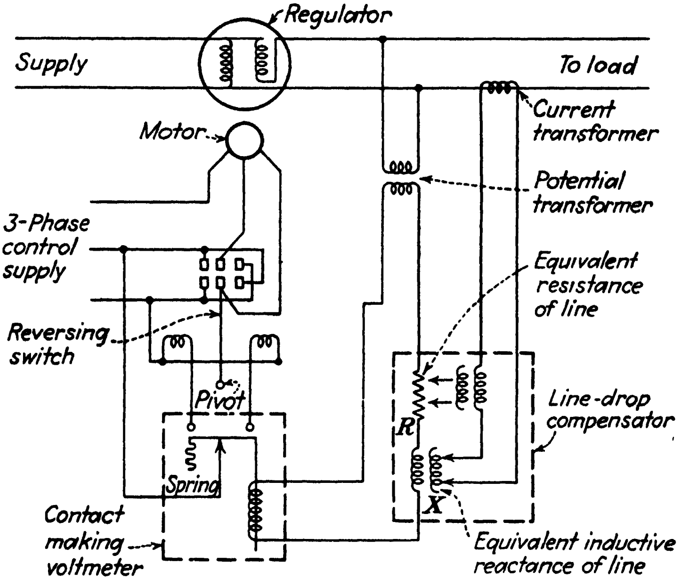


FIG. 109.—Diagram of control of induction voltage regulator.

A brake on the motor drive shaft prevents overrun past the point where the motor is stopped. Limit switches, at each extreme position of travel of the regulator shaft, are set to open the motor control circuit for travel in that direction. Many refinements of this arrangement are included in modern regulators, but fundamentally they are as outlined here.

Regulator operation is determined by the compensator and contact-making voltmeter adjustments. It is usual practice to select some point on the distribution feeder, such as the approximate center of load, and set the adjustments to give constant voltage at that point. Periodic checks are essential, by means of a recording voltmeter chart, to maintain this condition with load changes on the feeder.

With single-phase regulators and four-wire feeders, a closer control is possible with a practice known as *phase-area* connection of transformers. All the single-phase transformers near the substation are connected, for example, between phase 1 and neutral, those farther out are connected to phase 2 and neutral, and on the outer end they are connected to phase 3 and neutral. Settings of the compensators can then be adjusted for each of these sections of the feeder to allow for differences in the voltage drop to the sections. This is, of course, of most advantage for the longer, less densely loaded feeders and less important for the short feeders.

SUMMARY AND PROBLEMS

Voltage drop and heating effect of the current are the two principal factors determining design of all electric circuits. Safe carrying capacity of the conductors is of first importance in interior wiring, and in cables, transformers, and other parts where heat expulsion from around the conductor is limited. With overhead circuits and open wiring, voltage drop may be the limiting factor, and it is also of definite importance in the design of interior circuits.

Voltage variations, with changes in the load, must be held within certain limits for satisfactory service. On many circuits, particularly overhead feeders, there is an economic advantage in providing voltage control to raise the limit of permissible voltage drop. Addition of voltage regulating equipment may require less investment than a change of the wire or complete rearrangement of primary distribution feeders to reduce variation.

Selection of the method is largely a question of comparison for the particular condition. Many studies have been made, but generalized conclusions are not entirely safe for every situation. One conclusion that may be used as a starting basis is: for an average distribution feeder, a 1 per cent increase in kilowatt-hour consumption results for each 1 per cent increase in voltage, when voltage is below normal during the load period.

This criterion can be used to determine the increased revenue obtained by better regulation on the feeder.

Regulating equipment can be used to raise the general level of voltage and vary it with load variations, but it is of little help in overcoming fluctuations that occur abruptly. Motor starting currents, spot welders, and reciprocating loads are too fast in changing current for any present regulating equipment. Selection of wire size and arrangement of circuits are most important where loads of this type are served along with lighting.

In this connection, it is important to note the relative contribution to voltage drop of primary feeder, secondary main and services, and inside wiring. Few motors, served by residential area feeders, are large enough to affect the primary voltage. Most fluctuation is caused by motors on the same transformer and secondary main. On a well-maintained system, which has been rearranged to keep pace with load increases, the majority of fluctuations will be found to be caused by small motors on the same service or interior wiring system. For example, a branch circuit of No. 14 wire with 25 ft. between service entrance and a refrigerator has the same impedance as about 300 ft. of No. 2 secondary main.

Problems:

1. The voltage drop of the line in Prob. 4, page 96, was found to be excessively high for good voltage service, and some form of control would ordinarily be required. If the minimum load on this line is 300 kw., what range of voltage control would be needed to maintain voltage at the load within 3 per cent of normal at all times?

2. If the load of Prob. 4, page 96, is served by a 13,200-volt three-phase line with the same spacing, but with No. 2 wire, what is the voltage regulation?

3. Check the statement of the last sentence in summary above—with 8-in. spacing of the secondary main.

4. A domestic refrigerator draws 16 amperes at 50 per cent power factor from a 120-volt line, when starting. The customer's service is 100 ft. long of No. 8 wire, and the distribution transformer is a 5 kva. having a resistance of 0.08 ohm and a reactance of 0.04 ohm at 120 volts. What will be the percentage voltage drop at the end of the secondary and at the customer's main line switch when the refrigerator starts if there is (*a*) 300 ft. of No. 6 secondary? (*b*) 500 ft. of No. 6 secondary? (*c*) 500 ft. of No. 2 secondary?

5. A 25-hp. three-phase induction motor that draws 65 amperes full-load current at 240 volts is to be supplied from a 4,160-volt feeder over 2 miles of No. 00 copper and ½ mile of No. 6 copper. Impedance of the supply to the feeder is 0.5-ohm reactance at 4,160 volts. When starting at full voltage (without starter), the motor draws five times full-load current at 40 per cent P.F. If the voltage dip during starting must be less than 3 per cent, can the motor be installed without a starter? (Equivalent spacing is 46 in.)

6. A 5-hp. 240-volt single-phase induction motor is to be served by 5 miles of No. 6 wire 2,400-volt line, with spacing of 76 in. Full-load current of the motor is 25 amperes, and starting current is five times this value at 50 per cent power factor. What is the percentage drop in the primary line if the motor is started without a starter?

CHAPTER XI

CURRENT INTERRUPTING EQUIPMENT

In previous chapters, we have been considering the normal flow of currents, at normal voltages, to supply loads. The amount of current flow depends on the amount of load, and the voltage depends on the supply to the circuit from generator or transformer. Wire and equipment sizes and capacities are determined by the normal flow of current and the allowable drop in voltage.

In this chapter, we are considering means by which current flow to the load may be stopped or started, either at the will of the operator or automatically in case of trouble. With automatic features, this equipment is to prevent the flow of abnormal currents which would cause damage to the conductors, equipment, or surrounding materials. In the next chapter, we shall consider means of preventing damage by abnormal voltage Excessive voltages are one cause of insulation breakdown Such breakdown causes faults or short circuits, which, in turn, allow abnormal currents to flow.

There are three classes of equipment in this group: (1) switches, (2) fuses, (3) relays.

Current interrupting equipment must be selected for the normal service requirements, for the current and voltage of the line and load to which it may be connected. In addition, there are two other requirements that must be considered:

1. Time and current characteristics, that is, the time to open the circuit for a given current to be interrupted.
2. Fault or short circuit current to be interrupted, depending on the supply system ahead of the location of the interrupting equipment.

Switches may be (1) nonautomatic, to operate under normal load conditions; or (2) automatic, to operate under abnormal or fault conditions. For automatic service, control relays are included in the auxiliary equipment required. Fuses combine the service of switches and relays, where conditions permit their use.

Normally, the resistance or impedance of the load and equipment connected to the circuit limits the current that flows through the circuit. When the circuit conductors are placed in contact with each other, ahead of or in the load equipment, this limit is no longer present, and the only limitation is the impedance of the circuit up to the point of the fault and of the fault itself. An increase in supply capacity, installation of larger transformers, construction of a larger or a second line, or changes in the substation or transmission facilities to meet requirements for load growth may cause protective equipment to become inadequate.

Under fault or short circuit conditions, something must open to stop the current flow. It should be the first point of protection, to minimize the disturbance and outage on the rest of the system. Coordination of protection is, therefore, an important factor in the application of this class of equipment.

Many faults on outside supply lines, overhead wires, or underground cables may "burn clear," without disturbance and without other interruption. This is particularly true with the lower voltage circuits. On the higher voltage circuits, many faults are self-clearing if the current is interrupted momentarily. All these possibilities must be considered in the selection and application of current interrupting equipment.

SWITCHES

Switches are used to open and close circuits. The simplest type is used at the meter board in our homes, to open the service to all wiring. As the next step, we might consider the quick break arrangement of the snap switch to control operation of lights and appliances. Following the same fundamental principles, we have disconnect and air-break switches on our higher voltage distribution lines and oil circuit breakers in our substations.

All switches must be designed to carry their rated current continuously without overheating. They must have clearances and insulation for the normal voltage of the circuit. They must be designed to open the circuit and break the current flow without damage due to arcing or flashover. Speed of breaking the circuit is a large factor in prevention of arcing between the opening contacts. Spring and snap action, arcing tips and auxiliary contacts, and insulating oil around the opening contacts are means used to minimize arcing. The principal types of switches for primary distribution use are outlined in Figs. 110 to 114. The symbols used on diagrams are shown beside the outlines of the devices.

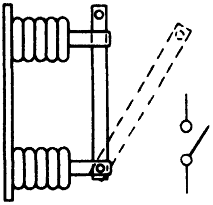


Fig. 110.—Disconnect switch.

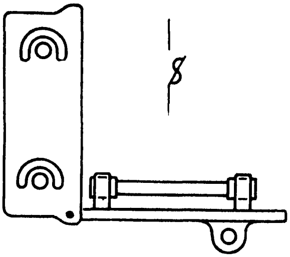


Fig. 111.—Fused cutout (in open position).

Disconnecting potheads and clamps are often used to isolate circuits in distribution systems. They can be used only after all current has been interrupted by some other means.

Disconnect switches (Fig. 110) are also used to isolate circuits. At low voltages, they can be used to interrupt load current, but arcing will occur with higher voltages. For example, the knife switches used on low-voltage switchboards will interrupt heavy currents, but disconnects on a distribution circuit will draw an arc with the same amount of current.

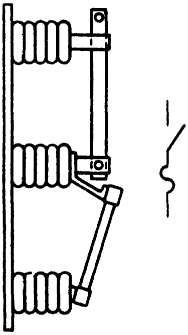


Fig. 112.—Disconnect fuse.

Fused cutouts are a special form of disconnect switch commonly used in distribution circuits. The fuse holder with its fuse link serves as the switch blade and is usually mounted on the housing door, so that opening the door swings the fuse clear of the contacts (Fig. 111).

Fused disconnects are used, in higher voltage distribution, where the cost of an oil switch for protection is not justified. The fuse may be mounted on the blade, or it may be placed on the load side of the disconnect switch, as in Fig. 112.

Air-break switches are a special form of disconnect switch, provided with an operating means for quick break between the blade and contact (Fig. 113). Arcing horns are placed on the blade and contact to draw out and break the arc. The switch is usually gang operated, to break the circuit in all conductors at the same time. In low-voltage circuits, the air-break switch can interrupt very large currents, and this type of switch has

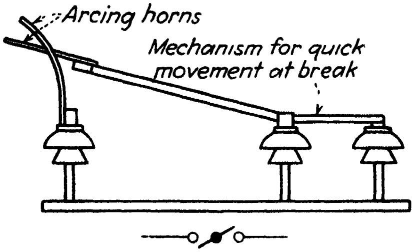


FIG. 113. –Air-break switch.

several advantages over fused knife switches or oil switches for industrial plant distribution. Recent developments have extended the use of air-break switches to high-voltage high-current applications also.

Oil circuit breakers, or oil switches, are the most dependable and most convenient to operate of any of the current interrupting

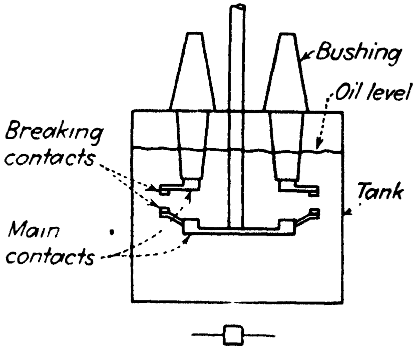


FIG. 114.—Oil circuit breaker.

equipment available for distribution and other high-voltage circuits. They are also the most costly; hence, their use is limited to those applications where other apparatus would not be satisfactory. This type of switch may be designed to interrupt any amount of short circuit current and to operate at any voltage. The arc at the time of current interruption is quenched in oil, which is totally enclosed in a steel tank (Fig. 114).

Oil switches are closed against the pressure of a spring or the weight of the moving parts and held closed by a catch or latch. Closing may be manual or electrical by solenoid magnet or motor. The switch is opened by release of the catch or latch. This release may be tripped either manually or by a magnet.

The service requirements of the switch determine the method of tripping used. If it is to open the load current only, it is designated as nonautomatic and is tripped by hand or by push-button control of the tripping magnet. Switches that are to interrupt overload and short circuit current are designated as automatic. Their tripping magnets are energized through the closing of relay contacts.

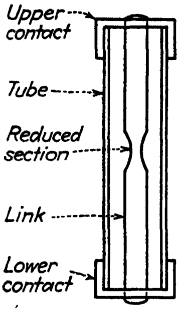


FIG. 115.—Link fuse in tube.

FUSES

Fuses are the simplest form of automatic overcurrent protection. They are made with a short section of metal with relatively low melting point or current carrying capacity. This melts and opens the circuit before the conductors reach a high temperature due to excessive current flow. Fundamentally, they provide means to control the location of breakdown and the amount of current to cause it, when abnormal current in the circuit starts to cause overheating.

The simplest type is the plug fuse, up to 30 amperes, used in the entrance switches and for branch circuits in our homes. In larger sizes, the link is in a tube with contacts at each end (Fig. 115). Originally, an open fuse wire link was used, but it is now enclosed for protection of the link and for greater convenience and safety in handling. Tin, lead, zinc, aluminum, and alloys of these materials are used. A short, reduced section of copper wire or strip is used for the same purpose in some applications. With low voltages, it is not difficult to prevent a flash or arcing at the contacts when the fuse wire melts.

The principle of fuses used on our primary distribution and transmission circuits is the same, except that when the reduced section melts there will be an arc or flash due to the higher voltage, and some mechanical means must be provided immediately to introduce a larger gap or spacing or to quench the arc.

Expulsion Fuses.—In this type of fuse, shown in simple form in Fig. 116, the arc is quenched by using the explosive action of the metal vapors and hot arc gases, with a principle similar to that of a gun. When the explosion caused by the arc and melting of the metal takes place, pressure is built up in the fiber tube, and the gases are blown or expelled out of the open end. This takes with it the bottom section of the fuse link and establishes a gap between the two contacts. The expulsion action is assisted by gas generated in the tube through oxidation or erosion of the tube walls. The explosive pressure depends on the amount of current interrupted, and fuses may be shattered and destroyed if the fault current is not considered in application of the fuse.

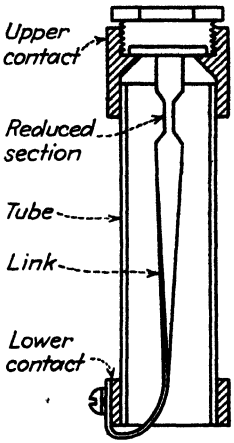


FIG. 116.—Expulsion fuse.

In the design of these fuses, the length and diameter of the tube are important, and a number of improvements have been made in the original expulsion fuses by careful check of these factors. In some designs, special attention has been given to the material of the tube walls, to increase the gas blast in the tube. One type has a compressed boric acid filler inside the tube.

Originally, fuse links were quite generally made on the job by cutting the proper length of fuse wire from a reel. These wires were furnished in different sizes for the ratings required. Factory built fuse links are now in general use, and they provide a much higher degree of accuracy. Instead of the reduced section of the link shown in Fig. 116, a short section of fuse material may be inserted in the main link and protected by an auxiliary fiber tube. As a further refinement, some types of fuse links are also provided with a small spring which assists in parting the sections and starting the interrupting action.

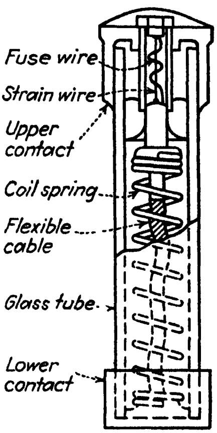


FIG. 117.—Liquid-filled fuse.

In another type of fuse, shown outlined in Fig. 117, the arc is quenched by a liquid within a closed tube. This action is similar to that in an oil switch in which the oil flows or is forced in to extinguish the arc. A coil spring is normally held in tension by a high-resistance tension wire. This wire is paralleled by the fuse wire, which carries the current. When the fuse wire is melted by high current, the tension wire is immediately melted also, releasing the spring, which contracts and pulls the contacts apart.

Application of Fuses.—The service conditions for which fuses are intended determine their application. There are two distinct groups of fuse requirements, even though these requirements may be interdependent:

In buildings, fire hazards from overheated wiring or appliances or from insulation breakdown in a cord, etc., determine the low-voltage fuse application. These fuses must be for the safe carrying capacity of the circuit and for prevention of fire. The safe current carrying capacity of No. 14 rubber covered wire, for example, is 15 amperes, and a 15-ampere fuse is used ahead of the branch circuit with this size of wire.

On primary circuits, coordination with other points of protection in series, prevention of interruption of service, and reduction of system disturbance are also factors of proper fusing. A principal function of the fuse in a primary lead of a distribution transformer is to disconnect that transformer from the line in case it is in trouble, without causing an interruption on other parts of the feeder also.

Transformers will stand short time overloads of several times their normal rating without danger, if in good condition. Fuses should not blow on these short time overloads or with momentarily high currents caused by motor starting. It may also be unnecessary for them to blow with the lower values of fault current caused by short circuits through high resistance on the secondary, which may burn clear without other damage. A fuse rating of two or three times the full-load current of the transformer is common practice. This basis is referred to as short circuit protection, and it is sometimes even higher for small transformers, although lower for the larger sizes. It is consistent with practical operation, holding interruptions of service to a minimum and yet affording a reasonable degree of protection to the transformer.

RELAYS

Relays are used in conjunction with switches to give automatic control of their operation. Relays pass along from one circuit to another any impulse given to the first circuit. In the most common application, current from a transformer in the primary line passes through the relay. If the current exceeds a set value, the relay closes its contacts, which closes the circuit to a tripping coil on the switch and causes the switch to open the primary circuit.

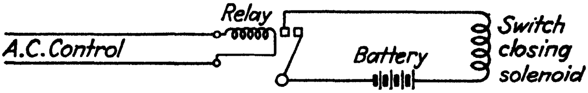


FIG. 118.—Elementary relay control.

Relays are used for many automatic operations. A simple arrangement is shown in Fig. 118. Many arrangements are in use which carry out a whole series of operations, waiting for proper action of each operation before going on to the next, in as orderly a fashion as a human operator could and with more precision. Probably the first use of the relay idea was in telegraphy, where repeaters were necessary at intervals in long lines, and relays are the basis of the present automatic telephone system.

Relays of the magnet-armature type of Fig. 118 are used mainly as auxiliary relays. The switch-closing solenoid requires a high current, and the battery and relay are located near the switch. The control circuit, requiring a low current, can be extended to a distant point, to a push button, or to another relay.

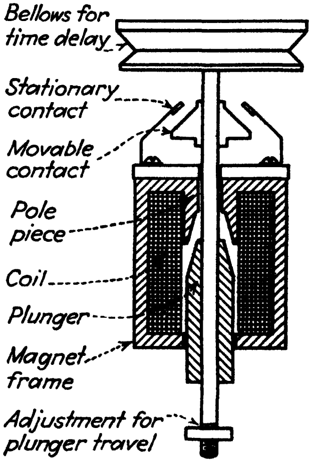


FIG. 119.- Plunger-type relay.

In another type of relay, a plunger moves in the center of an operating coil or solenoid (Fig. 119). The action of the solenoid draws the plunger upward, carrying the movable contact with it. Taps may be brought out of the operating coil to give a current adjustment, or an adjustment may be made in the amount of plunger travel, to vary the current necessary to start the movement. Time delay may be obtained by a dash-pot action using oil in a cylinder or by a bellows in which the air must be exhausted through an adjustable valve.

Induction-type relays are the most reliable and most widely used for protective application. As shown in the sketch of Fig. 120, a metal disk is free to rotate in a magnetic field produced by windings on a steel core. The shaft of this disk carries a contact that may swing around to a fixed contact and close a circuit. The disk operates against the tension of a spiral spring. The speed of rotation of the disk depends on the current flow in the coil winding, and the time to close the contacts can be adjusted by setting the initial position of the disk. The amount of current required to operate the disk against the springs can be adjusted by taps in the coil winding, similar to transformer winding taps. If this spring and the contacts were removed and the disk allowed to rotate freely, a rough form of induction meter would result. The shaft could then be connected to a dial register to count the revolutions of the disk.

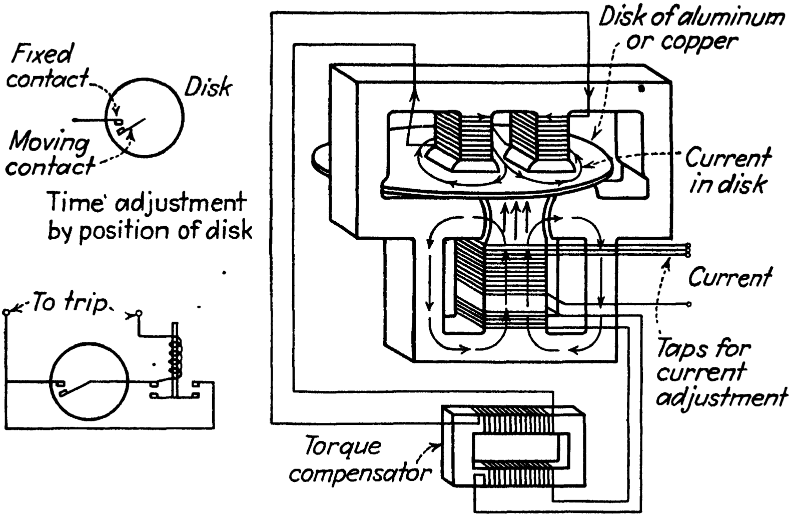

Fixed contact
Disk
Moving contact
Time adjustment by position of disk
To trip
Disk of aluminum or copper
Current in disk
Current
Taps for current adjustment
Torque compensator

FIG. 120. - Elements of the induction-type relay.

Other types of relays may be used in conjunction with the overcurrent relays. A power directional relay will close its contacts if the power flow in the main circuit is in a direction opposite to that for normal operation. Differential relays, impedance relays, temperature relays, reverse phase relays, polarity directional relays, and other selective relays are used on network loops and other special circuit applications.

A common relay in use on distribution circuits is for reclosing of the switch when it is operated by overcurrent. When the main switch opens, an auxiliary contact starts a timing action in the reclosing relay, and after the correct time delay, a contact, operating through a closing relay, closes the main switch.

Reclosing relays for use on distribution circuits are usually arranged to reclose the oil switch or breaker three times, at predetermined adjustable intervals, and then lock out if the breaker trips a fourth time within the time interval. It is often possible to improve service continuity further by reducing the time for initial reclosure to a few cycles, or practically instantaneous. Many distribution line faults are of such a nature that interrupting the arc for as short a time as one cycle is sufficient to clear the fault and allow reclosing of the breaker and the service.

Instrument transformers are used in connection with relay circuits, as well as for metering. Because the relays and meters are essentially for switchboard use, low voltages and low currents are best suited for their operation. The standard for potential windings of relays is 110 volts, and the standard for current windings is 5 amperes. Potential and current transformers are used to insulate the instrument from the line and to supply this voltage and current. For example, a 13,200-volt line with a full-load current of 300 amperes might be provided with potential transformers of 13,200/110-volt ratio and current transformers of 300/5-ampere ratio for metering and protective instruments. The voltage ratio is then 13,200 to 110, or 120 to 1, and the current ratio, 300 to 5, or 60 to 1. Kilowatt-hour meters on this installation would carry a constant of 120 times 60 equals 7,200.

TIME-CURRENT CHARACTERISTICS

Many relays and all fuses have the characteristic that the greater the current, the less the time required to operate. The values of time to operate, at various values of current, are determined by tests and plotted on a curve sheet. The importance of these values in applying fuses and relays has increased with expansion of the distribution system, requiring closer coordination of all current interrupting equipment. Because of the many points of protection in series on a large system, this coordination must extend all the way back to the relays in the generating plant.

Current overload relays have two adjustments—coil taps for current and a lever for time. Current taps may be for 4, 6, 8, 10, and 12 amperes. With a 300/5-ampere current transformer and a tap setting of 8, the relay would have a current setting of 300/5 times 8 equals 480 amperes. To interpret the time setting, we must refer to time-current characteristic curves of the particular type relay. Curves for three lever settings are shown in Fig. 121. If, in this example, the time lever is set at 1, the time to close the relay contacts with a short circuit current of 1,000 amperes, or about 200 per cent setting, will be one-third second, taken from the curve.

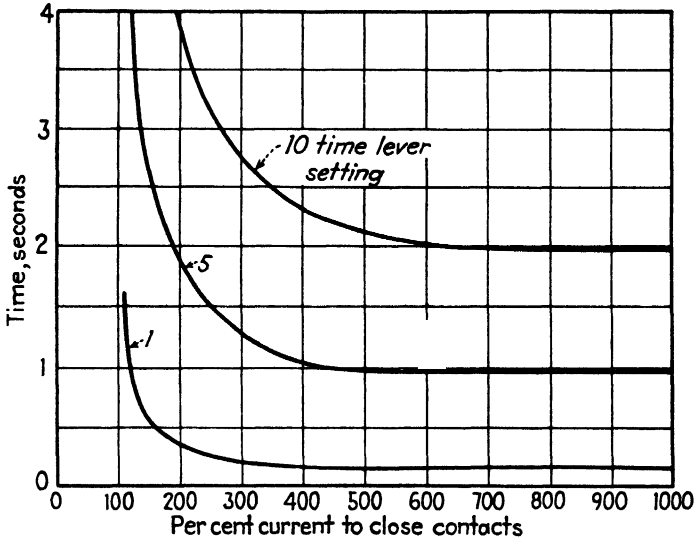


FIG. 121.—Typical relay curves of time-current characteristics.

Coordination of these characteristics means that, at all values of short circuit current, the fuse or relay nearest to the fault in the supply line will function first. It also implies that fuses and relays farther back in the line will give those in series toward the load time enough to function. Within recent years, much more attention has been given to this coordination problem than formerly, and as a result, many fuses have been redesigned and many fuse and relay applications have been changed.

Figure 122 shows an example of the curves used for this purpose. Fuse B on a feeder with Relay 1 setting would function properly with a high fault current, or with a low fault current, but under some conditions of fault or fault location, the relay would operate first. This would cause an interruption of service to all customers served by this feeder. Changing the relay setting to give the curve Relay 2 is one solution. Selection of a fuse with the characteristics of Fuse A is the alternative solution.

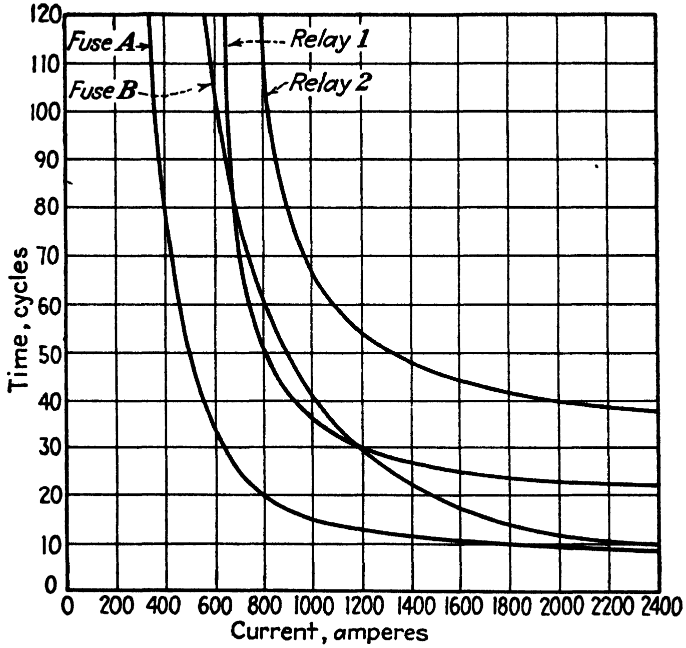


FIG. 122 —Coordination of fuse and relay characteristics

Fuses of different sizes must also be coordinated where main line sectionalizing points or branch lines are fused. Failure to coordinate properly all fuses with each other and with the main feeder relays may result in prolonged outages. Patrolling of the line must then be resorted to, to find and clear the trouble. In this connection, the importance of proper field installation of fuses should be noted. Even a well-coordinated plan of fusing can be defeated if the wrong size of fuse is installed, or if it is improperly installed at any point. An example of coordination curves is shown in Fig. 123. This is for two sizes of fuses in series and further in series with a substation relay-controlled oil switch.

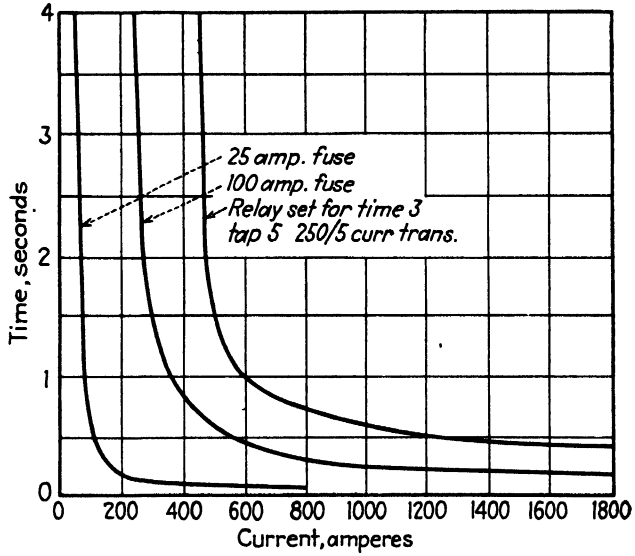


FIG. 123 Example of relay and fuse coordination

FAULT CURRENTS

In applying any protective equipment for interruption of current flow to a short circuit or fault, the maximum current that can be expected at that point must be determined. Calculation of this current follows the same principles that have been outlined for calculation of voltage drop. It must be remembered that when a short circuit occurs, the current depends on the voltage supplied, and the impedance to the point being considered. Under this condition, the voltage drop is from that supplied, *to zero*, instead of to the load voltage.

A short circuit is a transient condition. There is an inrush of current to any point where a short circuit or ground fault occurs. The majority of faults that occur on distribution feeders are between one phase wire and ground, such as in the case of the wire rubbing against a guy wire, against a tree limb, or the breakdown of an insulator, transformer bushing, or transformer winding. In other cases, however, two of the phase conductors may come in contact, and, in the most severe case, the three-phase conductors are short-circuited together, causing a three-phase short circuit on the system.

We may first consider a simple case, as shown in Fig. 124, in which resistance only is considered to limit the current flow. It is assumed, for this illustration, that the generator is large enough to maintain rated voltage through the fault condition.

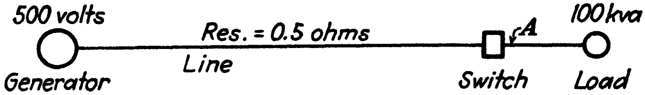


FIG. 124.—Simple case of fault (at A) with resistance only.

By applying the principle of Ohm's law, the current with a fault at point A is

$$I_F = \frac{E}{R} = \frac{500 \text{ volts}}{0.5 \text{ ohm}} = 1{,}000 \text{ amperes}$$

For comparison, the load current is found as

$$I_L = \frac{100{,}000 \text{ volt-amperes}}{500 \text{ volts}} = 200 \text{ amperes}$$

Relays on this switch would be set to operate at some value above 200 amperes and less than 1,000 amperes. A switch would be selected that would carry 200 amperes continuously without overheating and that would interrupt 1,000 amperes without in any way being damaged.

For calculation of fault currents in the usual alternating current distribution circuits, we need the tools discussed in Chap. VII, for finding voltage drop. Actually, the reactance part of impedance is often so much more important than the resistance part, in finding fault current, that the resistance can be omitted to simplify the calculations. In these calculations, we do not need to be nearly so accurate as in voltage drop and regulation problems, because we are dealing with relatively high values of current, and often as much as a few hundred amperes more or less will not greatly affect the selection of a switch. For the sake of safety, we should not work too close to the calculated value, just as we would use a rope that is on the safe side in strength and not just strong enough to get by.

Example: A 2,400-volt single-phase transformer winding failed, and the current must be interrupted by a primary fuse. Find the current under the following conditions. Impedance to the source of this line is 0.5 ohm. Wire, No. 2, spaced 2 ft. Distance to transformer: (1) at the point of supply, (2) ½ mile away, (3) 1 mile, (4) 1½ miles.

$$R = 0.161 \text{ ohm per } 1{,}000 \text{ ft.}$$
$$X = 0.126 \text{ ohm per } 1{,}000 \text{ ft.}$$

Solution: $Z = R + jX = 0.161 + j\,0.126 =$ (from coordinate chart, Appendix) 0.204 ohm per 1,000 ft.

1. At point of supply, $Z = 0.5$ ohm

Fault current is

$$I_F = \frac{E}{Z} = \frac{2{,}400}{0.5} = 4{,}800 \text{ amperes}$$

2. At ½ mile point

Z of ½ mile of line =

$$2 \text{ (wires)} \times 0.5 \text{ (mile)} \times \frac{5{,}280}{1{,}000} \times 0.204 \text{ (ohm)} = 1.08 \text{ ohms}$$

Adding this to the impedance to the supply point;

$$0.5 + 1.08 = 1.58 \text{ ohms}$$

Fault current is

$$\frac{2{,}400}{1.58} = 1{,}520 \text{ amperes}$$

3. At 1 mile point

$$Z = 0.5 + 2 \times 1 \times \frac{5{,}280}{1{,}000} \times 0.204 = 2.65 \text{ ohms}$$

$$\text{Fault current} = \frac{2{,}400}{2.65} = 905 \text{ amperes}$$

4. At 1½ mile point

$$Z = 0.5 + 2 \times 1.5 \times \frac{5{,}280}{1{,}000} \times 0.204 = 3.73 \text{ ohms}$$

$$\text{Fault current} = \frac{2{,}400}{3.73} = 640 \text{ amperes}$$

This is not strictly accurate, since, to be exact, the angle of the 0.5-ohm impedance must be known and added to the line impedance as resistance and reactance. It is sufficiently accurate for this type of problem, however.

Transformer impedances are determined by test, as outlined on page 107, and the values are given on the nameplate or in manufacturers' data. They are in terms of percentage of rated voltage necessary to circulate rated full-load current through the transformer windings when one coil is short-circuited and voltage is applied to the other. A formula is necessary to convert the percentage values to ohms. It is

$$Z \text{ in ohms} = \frac{Z \text{ per cent} \times E^2}{100 \times VA \text{ rating of transformer}}$$

As an example, take a 50-kva 2,400- to 240-volt single-phase transformer with 3 per cent impedance

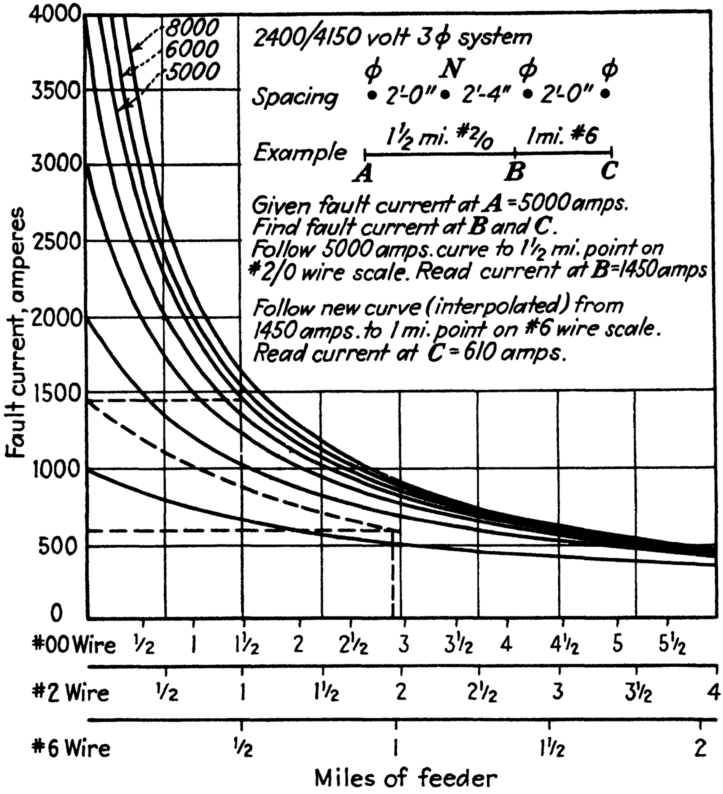
$$Z \text{ at } 2{,}400 \text{ volts} = \frac{3 \times 2{,}400^2}{100 \times 50{,}000} = 3.46 \text{ ohms}$$

Equivalent impedance or reactance of a transformer or line at another voltage is found by multiplying the known impedance or reactance by the square of the voltage ratio. For the preceding transformer

$$Z \text{ at } 240 \text{ volts} = 3.46 \times \left(\frac{240}{2{,}400}\right)^2 = 0\ 0346 \text{ ohm}$$

$$\left[\text{NOTE: } \left(\frac{240}{2{,}400}\right)^2 = \left(\frac{1}{10}\right)^2 = \frac{1}{100} = 0.01\right]$$

System Impedances.—The calculation of impedance from the generating plant to a distribution substation bus is usually quite complicated, because of the network of transmission lines and transformer banks to be considered. These values are usually determined and tabulated for major points of supply on the system, and from them distribution and relay protection calculations can be made by extension on the particular line. The impedance to any point on the distribution feeder is then considered in two parts: (1) the impedance to the substation bus and (2) the impedance of the line from the substation to the point considered. For the more complicated systems, a calculating test board is used, with all major lines set up in miniature equivalent reactance values, from which fault current readings are obtained for the main substation buses.



2400/4150 volt 3ϕ system

Given fault current at A = 5000 amps. Find fault current at B and C. Follow 5000 amps. curve to 1½ mi. point on #2/0 wire scale. Read current at B = 1450 amps

Follow new curve (interpolated) from 1450 amps. to 1 mi. point on #6 wire scale. Read current at C = 610 amps.

Fig. 125.—Variation of fault current on primary feeders.

STATION	FEEDERS	MAXIMUM FAULT CURRENT			MAIN LINE WIRE	CURRENT TRANS			RELAY TAP SETTING			AMPS. TO RELAY	RELAY TIME SETTINGS		HIGH VOLTAGE			BANK SIZE
						200	300	400	6	8	10		1A	CO	13.2KV O.C.B.	13.2KV. FUSE	33KV FUSE	
BRIGHTON	ABCDE	6400			00		X			X		480	3.9		X			6000
EVANSTON	AB	5450			00		X				X	600		1.5	X			3000
FT. THOMAS	A		3600		2			X	X			480	0.5			300		3000
HARRISON	A			700	6												50	225
MT. WASH'N	A		2180		2		X		X			360		3.6			100	1500

Fig. 126.—Tabulation of system characteristics.

When a large number of line or feeder fault current calculations are to be made, a chart or set of curves can be used to advantage. The curves shown in Fig. 125 are for a particular line construction, and their use is illustrated by the example. Miles of line are substituted for the corresponding values of impedance, and the fault current at the substation bus or any other starting point is used instead of impedance to that point.

To tabulate station fault currents, relay settings, and other data necessary in fuse and relay coordination, a table along the lines of the section shown in Fig. 126 will often be useful.

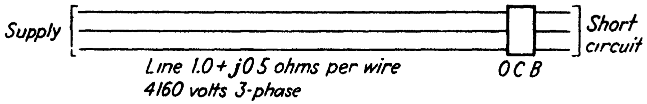


Fig. 127.—Example for three-phase short circuit calculation.

Three-phase faults have the same relationship to total power that is used in ordinary current and power calculations. *For example,* in Fig. 127, there is a total impedance per wire

$$R + \mathrm{j}\,X = 1.0 + \mathrm{j}\ 0.5 \text{ ohm}$$

between the supply point and the oil switch. From the coordinate chart (Appendix),

$$Z = 1.115 \text{ ohms}$$

Line is 4,160 volts, three-phase, or 2,400 volts phase to neutral. Fault current is

$$I_{SC} = \frac{E}{Z} = \frac{2{,}400}{1.115} = 2{,}150 \text{ amperes}$$

Total three-phase fault power is

$$\begin{aligned}\sqrt{3} \times E \times I_{SC} &= \sqrt{3} \times 4{,}160 \times 2{,}150 \\ &= 15{,}500 \text{ kva.}\end{aligned}$$

For a three-phase oil switch, an interrupting rating of 25,000 kva. would be the next higher standard rating.

Example of Calculation.—Short circuit calculations may be made with resistance of the line neglected. This method gives somewhat higher current values, which is on the safe side, and the approximation simplifies the work considerably. In the following example, a reactor is included at the substation, to hold the short circuit current on the line to within a definite limit.

Find the short circuit current on a 4,160-volt three-phase feeder supplied as shown in Fig. 128.

The total *reactance* of the system is the sum of the reactance up to the station bus, the 13.2-kv. line, the transformer bank, and the 4,160-volt line to the point of fault. We must remember to refer these to the same voltage base, that is, determine equivalent reactance at one voltage or the other for all parts of the circuit.

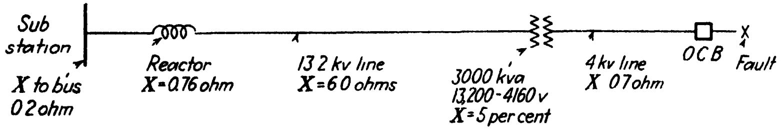


FIG. 128.—Example for short circuit calculation.

Solution: Total reactance X of 13.2-kv. circuit is
To bus: 0.2 + Reactor, 0.76 + Line, 6.0 = 6.96 ohms
At 4,160 volts, this 13.2-kv. reactance is

$$X \text{ at } 4{,}160 = 6.96 \times \left(\frac{4{,}160}{13{,}200}\right)^2 = \qquad 0.69 \text{ ohm}$$

Transformer reactance is

$$X \text{ transformer} = \frac{5 \times 4{,}160^2}{100 \times 3{,}000{,}000} = \qquad 0.286 \text{ ohm}$$

To these is added the 4,160-volt line reactance 0.7 ohm
Total reactance per phase, $X =$ 1.676 ohms

$$\text{Short circuit current, } I_{sc} = \frac{E}{X} = \frac{2{,}400}{1.676} = 1{,}430 \text{ amperes}$$

$$\text{Short circuit } VA = \sqrt{3} \times E \times I_{sc} = \sqrt{3} \times 4{,}160 \times 1{,}430 = 10{,}300 \text{ kva.}$$

A useful approximation that may be made is as follows: Short circuit current equals load current divided by the percentage voltage drop to the point being considered. For example, if a load current of 200 amperes causes a voltage drop of 5 per cent, the maximum short circuit current is

$$I_{sc} = \frac{200}{0.05} = 4{,}000 \text{ amperes}$$

Similarly, with a transformer supplying a load, the maximum possible power to be interrupted on the secondary is the kilovolt-ampere rating of the transformer divided by the percentage impedance of the transformer. (This neglects all supply line impedances.) For example, with a 1,000-kva. bank of 4 per cent impedance

$$\text{Secondary fault will not exceed } \frac{1,000}{0.04} = 25,000 \text{ kva.}$$

SUMMARY AND PROBLEMS

It is very important that we keep the distinction clearly in mind, when applying current interrupting devices, that fault or short circuit current does *not depend on the load,* but is determined by the *supply.* Thus, a load supplied by a 4-kv. line may require only a 50-ampere fuse, yet the current it must interrupt may be 5,000 amperes. An oil switch for a 1,000-kva. transformer bank may be required to interrupt 100,000 kva.

Fundamentally, it is desirable to clear a fault in the minimum possible time, so that the reduction of voltage and the resultant disturbance on the system will be as small as possible. However, the proper coordination of the time-current characteristics of all protective apparatus and devices must also be considered.

TABLE IV.—SUMMARY OF CURRENT-INTERRUPTING EQUIPMENT

Nonautomatic— To operate under normal load conditions	Knife switches Disconnects Snap switches Air-break switches Oil switches with manual control	
Automatic— To operate under abnormal or fault conditions	Oil switches	With current, power overload, directional, or special relay control
	Fuses	Simple melting action Mechanical separation Expulsion Gas or liquid for arc quenching

A summary of current interrupting devices is shown in Table IV. Requirements in selection of the device include:

1. Clearances, distance between conductors, insulation, and distance between the contacts when the switch is in an open position must be sufficient for the voltage of the circuit.

2. Size of the contacts and connections, and reduced section in the case of fuses, must be sufficient to carry the maximum normal load current without overheating.

3. Depending on the operating conditions, the device must open the circuit, without flashover, with current flowing.

a. Disconnects without quick-break arrangements may be for isolation only, and not to open load.

b. For nonautomatic operation, switches are required to break only the load current. Their interrupting rating depends on what is on the *load* side of their location.

c. For automatic operation, fuses and switches with relays are required to open the fault current. Their interrupting rating depends on what is on the *supply* side of their location.

Problems:

1. With a 200/5-ampere current transformer, tap setting of 6, and time lever setting at 1, what is the time to close contacts with 1,000 amperes current, with the relay characteristics shown in Fig. 121?

2. With the setting of Prob. 1 replacing that shown in Fig. 123, should a 100-ampere fuse be used on the load side of the relay? What would be the blowing time for the 100-ampere fuse at 1,000 amperes?

3. Referring to Figs. 125 and 126, what is the fault current 1 mile out on the main line of Ft. Thomas feeder *A*?

4. Find the short circuit current, if the 0.76-ohm reactor is removed, the transformer X is 3 per cent, and the 4-kv. line X is 0.1 ohm, in the example of Fig. 128.

CHAPTER XII

VOLTAGE PROTECTION—LIGHTNING—GROUNDING

Every electric circuit must be insulated to prevent flow of current over paths foreign to the circuit, either to surrounding materials or between conductors uncontrolled or unrestricted by load. Contact of two conductors, when there is voltage between them, allows current to flow. This will ordinarily be excessive, causing overheating or arcing, with resulting danger to the circuit or surrounding materials, as considered in the previous chapter.

All electric circuits are, or can be assumed to be, at a potential or voltage pressure relative to earth or ground, which is at neutral or zero potential. Breakdown of insulation of one conductor will, therefore, allow current flow from the conductor to ground, except in the case of a grounded or neutral conductor of the circuit. Earth is ordinarily a good conductor, and formerly some circuits operated with only one conductor wire, using the earth for return. This practice was never common for electric supply circuits, but was often followed for communication and signal circuits.

Commonly used insulators or nonconducting materials include porcelain, glass, fiber, rubber, cambric, and nonmetallic compounds. The exact nature and best material for insulation vary with both the voltage of the circuit and the surrounding conditions. Insulation has been the largest single subject of research in the whole field of electrical equipment manufacture and utilization.

From the standpoint of application in distribution, insulation may be considered under two headings: (1) insulation for normal voltage with materials that will not deteriorate and break down, and (2) protection from abnormal voltage that will break down the normal voltage insulation and allow power current to flow. The first part requires careful selection of materials, and the second part requires additional equipment and connections in the field.

Abnormal voltages are most commonly caused by lightning discharges, although internal conditions in the electric circuit sometimes cause surges of voltage. Another cause of high voltage is a breakdown of insulation on one circuit, which may allow voltage to get to a lower voltage circuit. This may happen if the windings of a transformer fail, or if a primary line breaks and falls across a secondary line.

Protection from these abnormal voltages is usually in two parts: (1) provision of a by-pass to carry the high voltage to earth without allowing it to travel over the circuit, and (2) provision of protective grounding connections on equipment. It is important to note that protection, after an abnormal voltage is on the line, involves connection to ground to drain off the voltage to a zero or neutral plane.

LIGHTNING

Lightning discharges in air affect our transmission and distribution lines more than any other external cause. On high-voltage transmission lines, a direct stroke to one of the conductors is necessary to cause damage, because of the normally high insulation level of the line. On lower voltage lines, including distribution feeders, induced surges may also cause trouble. Here, a discharge that does not strike the line itself, but hits a nearby tree or other point, may start a surge or wave along the line, which may be sufficient to overstress the normal insulation.

Until Benjamin Franklin made his kite experiments to prove that lightning was an electrical discharge, all sorts of superstitions were held, relating the flashes to the wrath of the gods and supernatural causes and omens. Until recent years, the explanation of what actually takes place, the magnitude of the voltages and currents, and the time required were mostly theoretical subjects. Now, owing to the development of measuring devices capable of measuring in millionths of a second and other devices to measure current flow of high values at short time intervals, it is possible to assign some definite values to lightning discharges and to surges caused by them.

When these values are known, more definite steps can be taken in design of protection against the damage of lightning discharges on electric lines and equipment. Another great step has been the development of laboratory equipment to create artificial lightning. With this apparatus, it is possible to test equipment being designed for use on transmission and distribution lines and to determine the benefit of changes in withstanding the high-voltage discharges. A full explanation of lightning theory involves a great deal of highly technical and scientific data and is not within the scope of our present study.

Lightning is the discharge of a heavy static charge of electricity from a storm cloud to earth. Electrical energy is formed in the storm clouds, and it induces a charge of equal quantity in the earth below it. These two charges are of opposite polarity; that is, one is positive and the other negative. When a discharge takes place, the energy stored in the cloud is dissipated to earth in the shortest possible time, and it seeks the lowest instantaneous breakdown path.

Lightning discharges are measured or estimated in millions of volts, but in millionths parts of seconds. Although the current is measured in thousands of amperes and the power is very great, the total energy is small. An interesting estimate gives these figures: 100,000,000 volts, 100,000 amperes, 1,000,000,000 hp., 10 microseconds (millionths of seconds). The energy represented in such a discharge is in the order of 4 kw.-hr.—not worth trying to harness and convert to useful purposes at our usual electric rates of less than 5 cents per kilowatt-hour.

Damage to equipment is due (1) to the breakdown of insulation caused by the high-voltage discharge, and (2) to the follow current of the normal voltage of the line. When the lightning surge breaks across an insulator, a heavy current flows, creating an intense heat. This heat is sufficient to crack porcelain insulators or bushings or to tear away fabric, rubber, varnish, or other insulation on wires or in windings. When the insulation is thus broken down, the normal voltage on a line can maintain a flow of current through this path. It is the excessive flow of the line current through the breaks that causes the line fuses or switches to open.

Artificial Lightning.—By use of an artificial lightning generator, it is possible to study and experiment on protective methods. Voltages up to one million are available in several laboratories and up to five million or higher in several others. This equipment is relatively new. The first five million-volt generator was operated in 1929. Within the past few years, measurement of actual discharges has been made possible on transmission lines. Thousands of measurements have been made in the field by means of instruments known as magnetic links and surge crest ammeters. Oscillograph tests have supplemented this information.

Lightning surges and waves are described by the time to reach crest or maximum value and the time to decrease to one-half crest value. Thus, a ½- by 40-microsecond wave means an impulse that rises to crest in ½ microsecond and decreases to one-half of the crest value in 40 microseconds from its inception.

LIGHTNING ARRESTERS FOR PROTECTION

Every time lightning discharges from a cloud, it is going to ground, and nothing can stop it. Our only protection is to put something in its path to help it get to ground around the equipment that we are trying to protect. Because our lines are up in the air and are closer to ground potential compared with the surrounding air, they may be hit, or lightning may hit nearby and induce surge voltage on the line. Lightning protection is, fundamentally, getting *a good path to ground* in parallel with the equipment.

Transformers and other equipment are designed to withstand a large rise in voltage above the normal operating value, but it is not possible to provide sufficient insulation so that they will not break down under the heavy surges resulting from lightning discharges. Lightning arresters must be able to operate and ground the line to drain off the lightning voltage surge, before the safe value of the equipment is reached, if the equipment is to be protected from flashover and damage.

Lightning arresters have two chief elements: (1) an air gap, or series of gaps, that will not flash over at normal line voltage, but will flash over with the voltages of the order of lightning surges, and (2) a material through which the discharge current flows to ground and which shuts off the flow when the voltage is reduced below the critical point. These two elements of the lightning arrester are enclosed in a porcelain tube or housing and sealed to prevent moisture entering, as shown in the outline of Fig. 129.

Materials that are used in lightning arresters do not follow Ohm's law. That is, their conductivity is a function of the applied voltage, increasing as the applied voltage increases. At low voltages these materials are substantially insulators, and at high voltages they are good conductors.

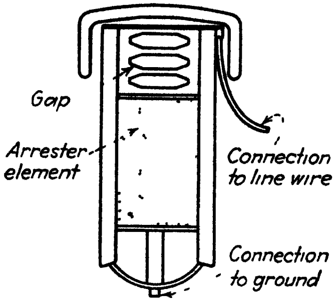


FIG. 129.—Elements of lightning arrester.

In operation, the lightning arrester serves functions somewhat similar to those of the mechanical pressure relief or safety valves of gas or steam systems. An arrester for a 4-kv. line may be designed to allow 8- or 10-kv. arc over its gap. There may be several thousand amperes in the surge current, and this flows out through the arrester element. This flow is stopped as soon as the voltage again drops to normal, and the gap normally isolates the line from ground. Similarly, a safety valve on a boiler, of which the normal pressure is 90 lb., may be set for 100 lb. If the steam pressure suddenly rises above this value, the valve opens and allows the excess steam to blow off. The pressure then decreases to below the critical point, when the valve closes.

Grounding connections and lightning arresters must function together, and the connection is as important as the arrester itself. During the time that the surge current is flowing, the arrester and the ground connection act as any other electrical conductor, retarding the flow of current in proportion to the resistance and impedance. For example, the resulting voltage drop across the ground connection, with a surge current of 1,500 amperes and a resistance of

100 ohms: 100 × 1,500 = 150,000 volts
50 ohms: 50 × 1,500 = 75,000 volts
20 ohms: 20 × 1,500 = 30,000 volts

To each of these voltage drops must be added the internal drop in the arrester. If it is 10 kv., the total for the preceding conditions would be 160 kv., 85 kv., or 40 kv. The critical point of a 2,400-volt transformer being protected by this arrester may be about 50 to 60 kv. With these conditions then, protection is afforded only if the ground connection resistance is about 30 ohms or less. There are, it will be noticed, several variables in applying arresters, and the results depend on the combination. Arresters themselves are sometimes wrongly charged with being ineffective, when it may be the connection made at the time of their installation that is at fault.

An upper preferable limit for ground resistance is often given as 15 or 20 ohms, to assure protection of weaker distribution transformers against the majority of lightning discharges. Higher values of ground resistance may provide adequate protection for the smaller discharges. However, for protection against the less frequent but most severe lightning discharges, a ground resistance of 5 ohms, or less, may be necessary.

TRANSMISSION LINE LIGHTNING PROTECTION

In the design of major transmission lines of over 66,000 volts, protection must be afforded against direct strokes of lightning. It is only in recent years that this conception has replaced the previously prevailing idea that most of the severe lightning surge voltages appearing on transmission lines were induced and that, therefore, the insulating level of the lines depended on the operating voltage.

Modern electrical design of a transmission line is practically independent of operating voltage and is based on the desired performance, as far as lightning is concerned. The main consideration is the protection level that must be secured and how it can best be obtained. Three fundamental factors are observed:

1. Sufficient insulation between the line conductors and the supporting structures.
2. Overhead ground wires so placed that they will intercept direct lightning strokes.
3. A low value of ground connection resistance.

A well-designed line must take these three factors into consideration and have them in a practical balance. How near lightningproof the lines will be depends largely on the justified investment in the protective design. Thus, a line may be designed on the basis of allowing two outages per year per 100 miles, with certain values of grounding resistance and insulation levels. It may be that a further increase to eliminate these two outages will add unreasonably to the cost of the line, compared with the value of their elimination.

When lightning strikes a transmission line, a surge voltage of several million volts is built up and flashes over the insulators, starting an arc between the conductor and the ground or tower. The normal line voltage continues this arc, damaging the conductor or the insulator, or both, and causes an interruption by opening of the line switch. Arcing horns or rings may be used to keep the flash away from the insulators (Fig. 130).

Expulsion tubes or flashover protector tubes may also be mounted at the insulator. An installation on a 220,000-volt line is shown in Fig. 131. An insulating tube is used, with an electrode at each end and a discharge vent at the lower end. The length of the tube is such that spark-over occurs across a gap between the two electrodes within the tube.

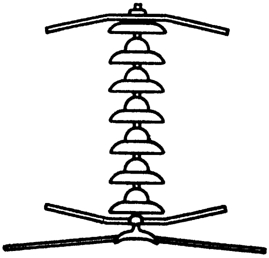


FIG. 130.—Arcing rings or horns to keep flash away from insulators.

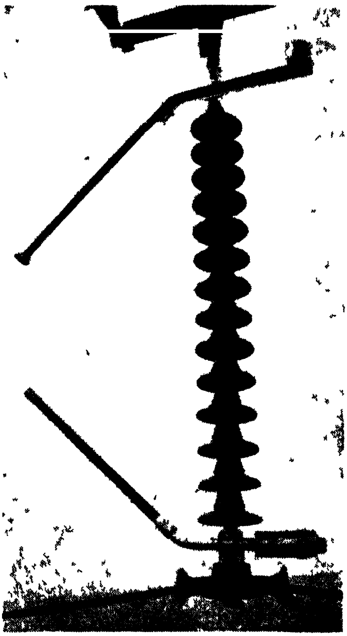


FIG. 131.—Expulsion tubes on 220,000-volt line.

A discharge across the external gap and through the internal bore of the tube prevents lightning flashovers across the line insulation. The attendant power follow current creates a high pressure within the tube bore, which expels the arc vapors from the discharge vents of the tube. The rapid expulsion action of the gases in the tube will normally interrupt the short circuit power follow current within the first or second half-cycle.

Ground Wires.—Since early days of transmission line design, it has been recognized that overhead ground or static wires (Fig. 132) were essential in holding down the number of flashovers and interruptions. It has been only within the past few years, however, that the full importance of low ground connection resistance and of shielding in the ground wire construction has been recognized. Conductors must be shielded from direct strokes, and grounding resistance must be kept so low that the lightning currents are unable to produce potentials high enough to flash the insulation, if an interruption-free line is obtained.

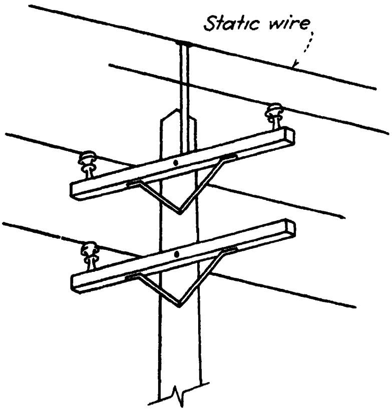


FIG. 132.—Overhead ground or static wire to protect transmission line.

A tower for two 66,000-volt circuits is shown in Fig. 133, with space for the second line to be installed later. Static wires are arranged to provide complete shielding of both circuits, and the insulators are provided with arcing rings. Grounding was closely coordinated in the design. This line was designed to permit one interruption per year per 100 miles, for the local conditions. As the line is 18 miles long, this means one outage in about five years.

When the necessity for low ground resistance was recognized in reducing insulator flashovers due to lightning, the first attempts were made to lower the resistance by means of driven rods. Later a wire was buried along the ground, giving in effect horizontal ground rods. This method is now referred to as the "counterpoise" and is extensively used to reduce lightning trouble. Such counterpoises may be continuous conductors buried a foot or two under the ground between towers, or they may be short sections of wire radiating out from the legs of each tower. In some cases, a double continuous counterpoise between the towers may be justified, and in still other cases both a continuous and a radial counterpoise system may be necessary to obtain reliable transmission line operation.

Extensive field investigations and laboratory tests have been made in the past few years on the subject of adequate protection for transmission lines. Reports and papers on designs and on the tests and experience results are contained in publications of the Edison Electric Institute and American Institute of Electrical Engineers. We must, however, refer to articles written in the past few years, and not to those of older date, for most of the present accepted ideas. The fundamental idea that we are interested in, in the present discussion, is that transmission lines may be designed to be practically lightningproof and that here, as in distribution equipment protection, a low resistance ground connection is absolutely essential.

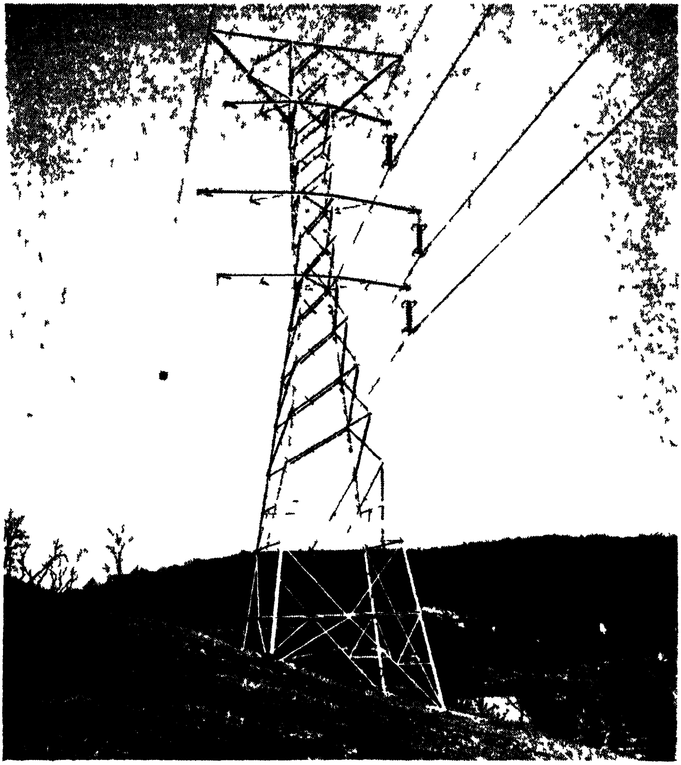


Fig. 133.—66,000-volt transmission-line tower.

PRINCIPLES OF GROUNDING

There are three principal functions of grounding: (1) to increase the safety to persons, (2) to increase the safety of equipment, and (3) to aid in system operation.

1. Structure, equipment, fences, and other parts of a substation that are normally not energized are grounded. Then, if they are charged owing to leaking or broken insulation, or because a line conductor has come in contact with the structure, the current will be carried to ground through these grounding connections. This prevents the body of a person coming in contact with the structure or fence, acting as a ground path. Switchboard frames, industrial equipment, and large appliance frames are grounded for the same purpose.

2. Lightning arresters and protective gaps connected to the line conductors must also be connected to ground, so that dangerous surge and lightning voltages and the follow current will be carried to ground. This is to prevent the breakdown of insulation and damage to the line conductor and equipment. Overhead ground wires may also be classed in this group.

3. Current carrying conductors may be grounded, as in the case of the neutral of a distribution circuit. This provides a definite path to ground for fault current, simplifies relaying, and permits more rapid isolation of faulty circuits. Secondary services and interior wiring systems have ground connections for similar reasons.

These three functions are served by two types of grounding connections: (1) by solid connection of one conductor, or of equipment that is normally in the circuit; and (2) through a gap or arrester of a conductor that is normally insulated from ground.

In substations and in large transformer installations, it is common practice to install a ground system consisting of a number of driven rods interconnected with a bus, to which may be connected all the station equipment and the neutral and other points to be grounded. With transformers installed on poles, such a grounding bus is not available, and single or multiple driven rods must be relied upon, or the grounding may be interconnected with the primary or secondary neutral. In any case, however, the individual driven rod becomes an important part of the grounding system.

Grounding of interior wiring systems is a very important safety and protective practice. There are two principal purposes for this grounding:

1. It serves to drain off to ground, through a definite connection, any voltage surges and current that may follow insulation

breakdown in the transformer serving the wiring or that may be induced by lightning discharges near the secondary or service lines.

2. It aids in protection by providing a path for fault current. When a phase wire becomes grounded in the interior wiring or appliances, a current will be drawn through the phase wire and ground connections, sufficient to open the fuse or switch. Without the grounding, the fault current may not be sufficient, and arcing or leakage may continue for a considerable time before being detected.

The National Electrical Code requires this grounding for interior wiring systems, to a water piping system, if available, and otherwise to driven rods. The usual arrangements are considered in the chapter on Transformer Connections. For single-phase services, the neutral wire of the three-wire secondary is grounded at the transformer and at all services, as shown in Fig. 74. For three-phase power services, the mid-point tap may be grounded, as shown in Fig. 98. The neutral conductor of three-phase 120/208-volt secondaries, as commonly supplied from network mains, is also grounded.

Driven rods are the most common grounding electrodes. These rods must be driven deep enough to reach below the permanent moisture level. By test, it has been found that 6 ft. is the minimum depth and that 8 ft. depth is ordinarily more economical and has advantages that make this length advisable. This greater depth permits penetration deeper into the permanent moisture level and helps to maintain the resistance at a more steady value. Variations of resistance for various depths for one grade of soil are shown in Fig. 134, which is taken from the U.S. Bureau of Standards, Technical Paper No. 108.

Wet, marshy ground and ground containing refuse are usually considered to have the lowest resistivity, and clay or loam or either mixed with small quantities of sand follow closely. Sand, gravel, and stone offer the greatest difficulties in obtaining low-resistance grounding.

Ground rod resistance is, by itself, in nearly all cases, an entirely negligible part of the total resistance of the ground connection. The resistance introduced by contact between the ground electrode and the soil is also generally negligible. The resistance contributed by the soil is the predominant part of the ground connection. This resistance is made up of all the multiple paths of the variable cross section through the soil that surrounds the ground electrode. Ordinarily, the greatest resistance is in the soil immediately surrounding the electrode. The character and condition of the soil at the particular point where the grounding connection is to be made are, therefore, of predominant importance.

Since the resistance of the ground rod itself is ordinarily negligible in the total resistance, the material of the rod is not important, as far as initial resistance is concerned. The material should, however, be selected to withstand corrosion. Although an ordinary steel rod or pipe would compare favorably with any other form of electrode, a copper or copper covered ground rod will ordinarily last longer.

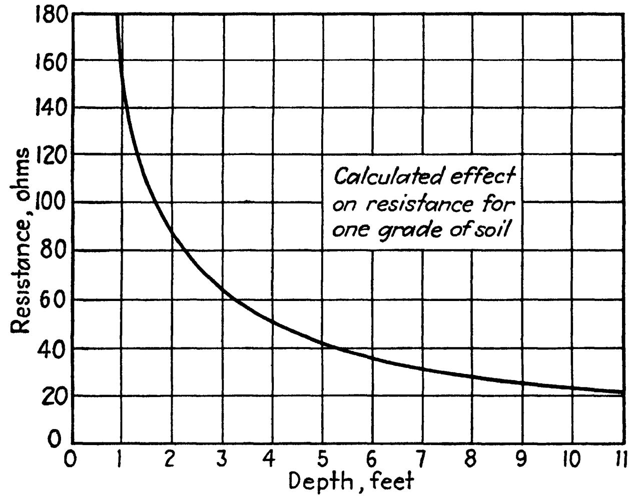


Fig. 134.—Effect of depth of ground rods.

When a rod is driven near a wood pole, for grounding equipment on the pole, it must be kept in mind that the earth surrounding the ground rod is the important part of the connection. This means that the ground rod should be several inches or a foot away from the pole, so that wood insulation of the pole does not prevent flow of current away from the rod. When it is necessary to drive a rod near a pole, it can be driven at an angle so that its lower end is away from the pole.

The diameter of the ground rod also has only a negligible effect on the ground resistance, and the resistance can be reduced very little by increasing the rod diameter, even over a wide range. The conclusion is that the ground rod should have a diameter only large enough to make the rod of sufficient strength for driving in the usual soil conditions, without bending or splitting the rod. Rods ½ to ¾ of an inch in diameter are most commonly used.

Multiple rods will often be necessary to obtain the desired resistance level. The approximate reduction in resistance obtained with two, three, or four rods in multiple, compared with the resistance of one rod, is shown in Fig. 135 (from U. S. Bureau of Standards, Technical Paper No. 108). It is recommended that the distance between driven electrodes should be not less than about 6 ft. This distance is necessary to keep each rod out of the dense current field of the others. Where a ground connection of low resistance is required, maximum economy is usually obtained by the use of multiple electrodes rather than by trying to obtain much greater depth.

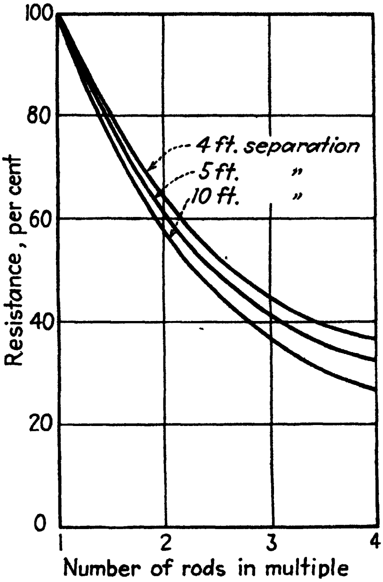


FIG. 135.—Effect of rods in multiple.

After installing a driven rod or any other ground, there is only one way to determine the protective value and that is by measuring its resistance. It is known that resistance may vary even in a given locality, between individual rods. Consequently, the resistance on every protective rod should be measured. This may be done with a voltmeter and ammeter or by means of a ground resistance measuring instrument, of which there are a number on the market. Exact determinations are not necessary, but it is important to know whether the resistance is of the order of 15, 50, or 200 ohms.

Soil treatment around the rod, to reduce the resistance to the smallest possible value, may be necessary in substations and other very important grounding systems. Common rock salt or magnesium or copper sulphate is the chemical generally used commercially for treating soil. The chemical is placed in a trench or excavation at the top of the rod. The effective life of treatment may be two or three years. By treatment, it is possible to reduce resistance from extremely high values, over 1,000 ohms, to 100 or 200 ohms. Soil treatment is not ordinarily justified, economically, for individual arrester grounding connections.

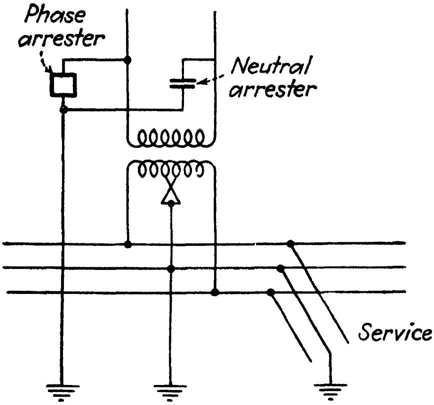


Fig. 136 —Separate grounding

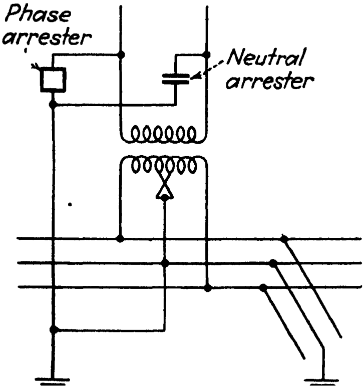


Fig. 137. —Interconnection of grounding.

Grounding Interconnection.—It was formerly common practice on distribution feeders to provide separate grounding connections for lightning arresters and for secondary main midpoint conductors (Fig. 136). The primary neutral was commonly grounded at the distribution substation supplying the feeder, but not at points along the feeder. A number of systems were operated, however, with all the grounding connections tied together or interconnected. A few years ago, extensive laboratory and field trial tests were made to determine the effectiveness and any disadvantages of the interconnection. This method of grounding (Fig. 137) has now replaced the separate grounding as the most common practice.

The original objection to the interconnection was that it made an electrical connection between the primary and secondary at the time the lightning arrester was carrying a discharge current. The laboratory tests and field experience have proved, however, that with interconnection there is less possibility of breakdown between high-voltage and low-voltage transformer windings or of flashover of the bushings, that might allow the primary voltage to be imposed on the secondary. The lightning arrester grounding connections are made much more effective by the reduction due to multiple grounding, and the surge voltage across the transformer coils is reduced to the surge voltage of the arrester itself.

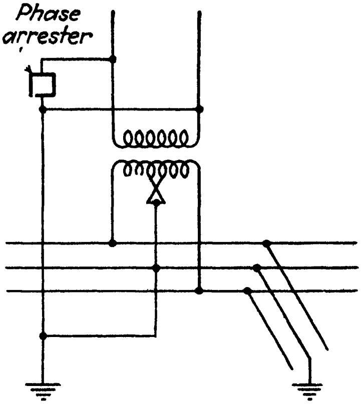


Fig 138 —Interconnection and with primary neutral multi-grounded.

The objection to multiple grounding of the primary neutral was from the standpoint of interference with communication circuits, especially where they depended on ground connections for signalling or as part of the circuit. Changes in these circuits, made for improvement in their operation, have largely removed this objection to distribution neutral grounding. Including the primary neutral in the grounding interconnection, as shown in Fig. 138, is now also becoming common practice.

Transformer cases are commonly grounded when they are in substations or on platforms. There is some difference of opinion regarding the grounding, where the mounting is on line poles. Grounding the case will generally help to reduce insulation stresses on the low-voltage winding, where there is a common or interconnected system. On the other hand, grounding the tanks may increase, in some measure, the possibility of shock should a lineman make simultaneous contact between the case and a line wire.

SUMMARY

The fundamental in protection from abnormal voltage is connection to ground, the zero potential plane. This is true in the case of a 120-volt appliance, and just as sure in the case of the highest voltage transmission line. For frames and structures surrounding or supporting conductors and for neutral conductors, the grounding connection is made solid and direct. For conductors that are energized, the grounding connection is made through a gap or arrester.

Abnormal voltages may develop due to breakdown of insulation, from internal surges, or because of external lightning discharges. Lightning is by far the most common and the most serious of these causes. When a voltage surge caused by lightning appears on a line, it is seeking ground, to dissipate its energy. If a transformer winding, an insulator, or other equipment offers the path of least resistance, the discharge will follow it to ground. This will usually result in breakdown of the normal insulation and permit power follow from the normal voltage supply. Protection from this possibility is to provide a detour or path around the equipment. This alternate path must offer lower resistance than the path through the equipment.

Included in the path for protective grounding is the resistance of the connection to ground—the ground electrode. The most practical grounding method is by rods driven into the earth. Their proper and effective installation is as important as the provision of lightning arresters, overhead ground wires, or arcing horns. The present trend of practice, and evident future method of grounding, is the interconnection of all points that are to be grounded. This method is being used for distribution transformer arresters, neutral conductors, and mid-point conductors of the secondary mains, as well as for transmission line tower grounding.

CHAPTER XIII

STREET LIGHTING CIRCUITS

Electric current was in use to supply street lights before Edison started to develop the incandescent lamp and later to apply electric service to lighting in buildings. The early lighting for streets was with carbon-arc lamps, supplied from special direct current generators. All the lamps were in series, and the generators were started when the lights were to be turned on and shut down to turn the lights off.

Improvements were made in the arc lamps, and a few arc light systems are still in use. With the general use of alternating current for other supply, these direct current arc lighting circuits were supplied through special transformers and rectifiers. Development of large incandescent lamps led to the more extensive use of alternating current circuits, eliminating the necessity for rectifiers.

Divisions of Street Lighting.—Full consideration of street lighting is logically in two divisions: (1) supply and control equipment and circuits, and (2) lighting fixtures with their lamps and glassware. Although each of these divisions naturally is dependent on the other in any consideration, light intensity and the proper use of reflectors, refractors, etc., under the second section are more in the field of the illumination engineer.

Supply circuits and equipment are usually an integral part of the distribution system. Separate lines for street lighting may be carried on the same poles or in the same duct system with general distribution. In other cases, the street lighting circuits are separate, supplying special lamp standards, but with supply to the transformers from general distribution primary feeders. With multiple circuits, the lamps are usually supplied directly from the same secondary that supplies residential or commercial services.

Illumination study involves spacing, size, and height of lamps, with special light distribution curves for comparison of various methods of mounting and application of glassware and other auxiliaries. Success in this field requires an expert knowledge not only of various technical factors, but also of our human reactions and satisfaction. Lighting requirements vary from merely indicating danger spots and intersections to bright boulevard and main business street standards. Vision may be accomplished by seeing persons and objects by silhouette or shadow against a lighted background or by direct light from the lamps.

Lamps for street lighting are rated in *lumens,* which refer to the amount of light given off by the lamp. The intensity of the light is expressed in *candle power.* Ten lumens are equivalent to one candle power. The efficiency of a lamp is expressed in terms of lumens per watt, that is, the amount of light output for the energy input to the lamp. Larger lamps are more efficient than the smaller sizes. Thus, a 600-lumen lamp operating at 6.6 amperes requires 42.9 watts, and the 6,000-lumen lamp requires 320.9 watts.

To increase light efficiency, various forms of reflectors and refractors are used. In reflectors, the light rays hitting the surface are stopped and redirected to the desired direction. Refractors are transparent, and the light rays hitting the surface are bent and pass through to the desired direction.

SUPPLY CIRCUITS

Supply to street lights may be from either series or multiple circuits. Series circuits and lamps are the most extensively used, and multiple circuit supply has a limited field of application.

Series circuits are in most general use because of the high efficiency for a widely distributed load. This supply permits a low current high-voltage circuit, using small wire with low loss and small voltage drop. Special transformers are required to supply constant current, usually at 6.6 amperes, and the voltage of the circuit depends on the number and size of the lamps connected.

Multiple circuits, with supply from the 120-volt secondaries, have two principal applications, which are at the opposite extremes of light installation density. In the case of a few lights in a section remote from other street lights, multiple lamps with a time switch may be used at less cost than a special transformer and circuit. In the central business section, street lighting may be from the commercial supply secondaries, with a pilot wire and relay control to turn them on and off.

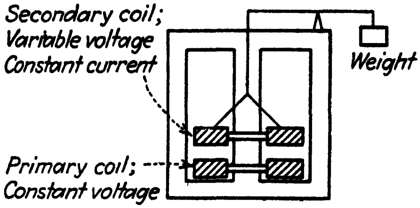


FIG. 139.—Outline of constant current transformer for street lighting supply.

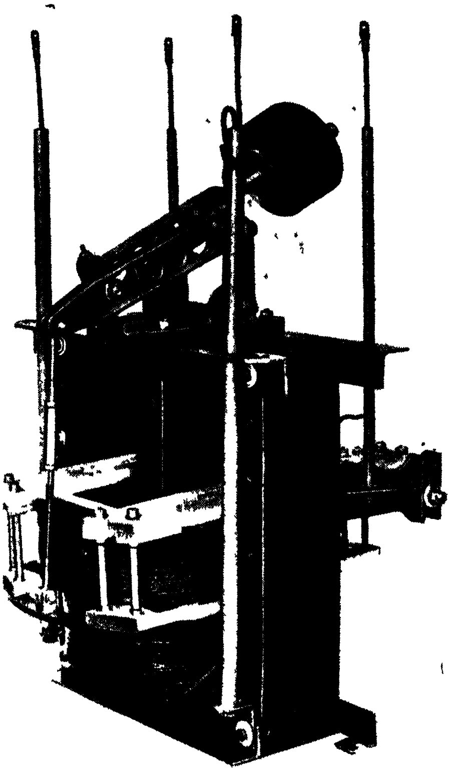


FIG. 140.—Constant current transformer ready for mounting in tank.

Constant Current Transformers.—Series circuits are supplied by transformers arranged to give constant current, with voltage varying to meet the varying load requirements. To obtain this from a constant voltage primary feeder, an automatic adjustment is arranged as a part of the transformer action. The constant current transformer consists of two coils mounted on an iron core, as in the standard transformer, but with one coil movable, as shown in diagram form in Fig. 139 and in the picture of Fig. 140.

The primary coil is fixed in position and receives power at constant voltage. The secondary coil is movable and regulates its position depending on the load. When it is close to the primary coil, most of the flux produced by the primary interlinks with the secondary, and the secondary voltage is maximum. The coils act as magnets and are wound to repel one another. If the load on the secondary decreases, an increase of the current follows and the repulsion between the coils increases. A weight is so adjusted that its pull, together with the force of repulsion, balances the weight of the secondary coil. With the increase of repulsion, the secondary coil is raised, increasing the leakage of magnetism between the coils. The secondary voltage therefore decreases, and its current drops to the required value

In Table V, a few values of transformer rating, number of lamps for full load, and secondary voltage are shown to illustrate the general data This is for 6 6 amperes straight series lamp circuits. Two values of transformer secondary voltage are shown—normal for full load and maximum with an open circuit.

TABLE V.—CONSTANT CURRENT TRANSFORMER RATING DATA

Kw	Normal volts	Open volts	Number of lamps of lumen rating				
			600	800	1,000	2,500	4,000
5	757	1,050	109	86	72	31	20
10	1,515	2,080	218	173	145	62	41
15	2,272	3,090	327	260	218	93	61
20	3,030	4,115	436	346	291	124	82

Data for General Electric Co. Type RO.

Constant current transformers are available for indoor use in substations, for pole mounting, and with subway-type cases for underground use. Because of building costs and congestion, there has been increasing use of pole mounted and subway installed transformers for the incandescent supply circuits.

Lamp failure, in the series circuit, causes a momentary opening of the circuit. In the socket of the lamp holder, a disk film cutout is in parallel with the lamp (Fig. 141). This is designed to puncture if the voltage across the contacts exceeds the normal drop through the lamp. When the film punctures, it allows the current to flow directly through the clips of the socket and restore the series circuit, with that lamp out of service. This results in a slight reduction in the load, and an adjustment is made by the transformer to reduce the total voltage of the circuit.

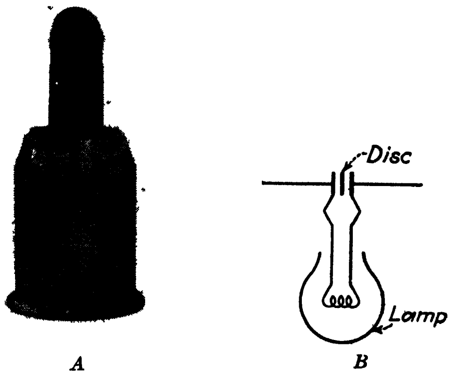


FIG. 141.—Socket for series circuit lamp. When the lamp fails, voltage punctures the disk and cuts straight through, with that lamp out of the circuit.

Higher current ratings, 15 amperes and 20 amperes, are often used for very large lamps, over 4,000 lumens. To obtain the higher current from the standard 6.6-ampere circuits, special transformers may be used at each lamp, connected as shown in Fig. 142. Where all the lamps of a circuit are of the higher rating, the supply may be at that current value to eliminate the use of transformers at each lamp. A cost comparison must be made for the particular conditions to determine which arrangement should be used.

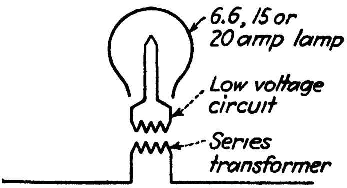


FIG. 142.—Series transformer to supply lamp at low voltage, from a series primary circuit

CONTROL EQUIPMENT

Selection and arrangement of control for switching lights on and off are among the most important problems in distribution to serve street lighting load. With the original systems, this was accomplished by starting or stopping the generator, and in later stages of the development, special transformers in the substations were connected to the substation bus through manually controlled oil switches. This requires a great many circuits from the substation, however, and congestion of wires on the poles near a substation may result.

A requirement for street lighting that sets it apart from supply to other loads is that it must be switched according to the length of the night. Schedules usually require sunset to sunrise burning of street lights, with possible seasonal variations from the actual time of sunset. This means that the switching time is different every day. With manual switching, this is very easily accomplished, but with supply from other points on the distribution system, automatic control or pilot wire control must be provided.

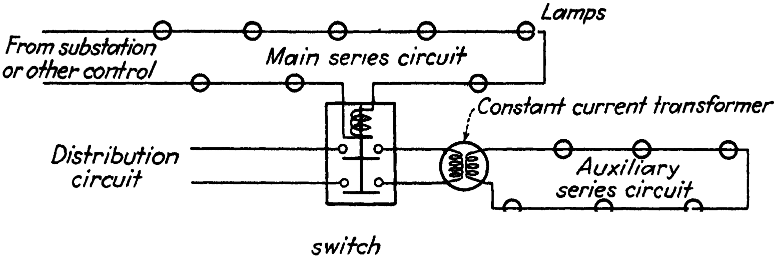


FIG. 143.—Series circuit control for extension of supply to further circuits.

Series control, or cascading, is one of the simplest methods of control. As shown in Fig. 143, the primary switch for a constant current transformer supply is equipped with an operating coil, in series with another circuit. Thus, a circuit originating at a substation to serve load in its vicinity may be made to control circuits that are added farther out or to provide capacity as load is added or the supply area extended. One circuit may operate several such switches, or switches may be installed in the second circuit for further extension.

Clock controlled switches are extensively used, especially for sections of street lighting supply remote from a main substation or other control center. Contacts controlled by the clock mechanism usually close a 120-volt circuit to a holding coil in the primary switch. Clock switches are often used to supply multiple street lighting circuits, by closing the main circuit directly through the contacts or by closing an auxiliary switch or relay.

An important refinement for this type of control is the addition of an attachment that moves the on and off contacts each day, to follow the changes in the length of days. Although offering many advantages over other types of control, the use of clock mechanisms, under the adverse conditions of pole or other outdoor mounting, has some disadvantages also.

Pilot wires offer a means of control for urban lighting. This plan may be used to control either series or multiple circuits, usually through relays or remote control switches of the type used for series control. The pilot wire circuit may be energized through the lighting period, to hold the various circuits closed, or it may be operated to carry a series of impulses. Different combinations of impulses are then used to close control switches and to open them. An important advantage of the impulse method is that different relays can be set to operate with different combinations, so that some circuits can be cut off at midnight while others are left energized all night, etc.

A separate primary feeder is sometimes used to supply pole mounted constant current transformers. This circuit is energized from the substation during the lighting hours and cut out of service at other times. In general, it is not so economical as pilot wire or other control arrangements, but, under some load conditions, it has important advantages. As constant current transformers provide their own voltage control, the use of a regulated primary feeder to supply these transformers may be wasteful of the regulated capacity. The separate feeder can be supplied from a section of bus in the substation that is not regulated.

Carrier current control is a relatively recent development. A special high-frequency current motor driven generator is operated at a central control point to send out impulses over the regular distribution circuits. Specially tuned relays connected to the secondaries of distribution transformers are operated by the high-frequency current. These control currents are superimposed for a few seconds on the primary lines by coupling at the substation, and they do not affect the standard frequency equipment or lights.

This system may also be used to control water heating or other load in customers' premises that is intended for operation during off-peak times. Several frequencies can be used, each controlling relays designed for that one frequency. The high frequency easily passes through standard transformers, and the current required is very small. At present, this equipment is quite expensive, and, therefore, must be justified by high density of controlled points.

Light intensity control, with photoelectric tubes or units, is another rather recent development. The light-sensitive tubes or units operate relays to control street lighting, so that the lights are switched on and off according to actual conditions, rather than according to expected sunlight conditions. This type of control is, like clock mechanisms, somewhat delicate for pole line mounting, but it has great possibilities for increasing use.

TRAFFIC CONTROL

Traffic control is a vital subject that is closely allied to street lighting as a public safety use of electric service. The switching of red, green, and yellow lights on a carefully predetermined schedule requires careful application of special control equipment. This control has largely superseded the traffic policeman at busy intersections and has extended this form of protection to many other intersections beyond the congested areas.

In the central business areas, traffic signals are usually supplied from a central control point. At other locations, individual controls are provided with service from the nearest secondary main. Special timing mechanisms are used, employing a small motor driving a contactor switch shaft. Supervisory control or a pilot wire may be essential to keep a group of controls synchronized or timed for even flow of traffic.

SUMMARY

Street lighting is an important application of electric service. It has many problems that are peculiar to it alone in the operation of distribution systems. Many safety studies and surveys have shown the great importance of adequate lighting in the prevention of crime and accidents on our streets. An increasing interest in this subject has accompanied the rapid increase in night automobile traffic.

Arrangement of lamps and their accessories usually requires a separate study in utilization, but supply to the circuits is part of distribution. Series circuits are most commonly used, but multiple circuits have a field of application also. Control for switching and the arrangement of circuits require cost and operating comparisons to meet local conditions. Both the particular lighting plan adopted and the distribution facilities for other load service must be considered in the layout for street lighting service.

CHAPTER XIV

MECHANICAL PRINCIPLES IN DISTRIBUTION

From the standpoint of work and investment in electric distribution, the application of mechanical principles plays a larger part than do the electrical considerations. The construction of pole lines, underground duct lines, stringing of wires, installation of equipment, and construction of steel towers, platforms, and structures require more men and more time than does the electrical connection of transformers and equipment.

Assigning only one chapter in this book to this subject does not, therefore, reflect its importance in the general subject of distribution fundamentals. Our principal approach has been, however, from the standpoint of the load, the general layout, and the capacity and size of equipment and circuits required.

A separate treatment of mechanical design includes the details of arrangement of the structures to carry the circuits to fit in with surrounding physical conditions. It involves a study of materials of construction, strength of such materials in the various forms in which they may be utilized, stresses to be encountered with consideration of safety to life, property and good service, and relationship with the property of other utilities.

For our present purpose, we can include only the fundamentals on which are based the designs incorporated in standards of construction and material specifications. Of these fundamentals, the computation of stresses in guying is the most frequently used, and it illustrates the principles involved in many more complicated structure design problems. Similar computations, together with those for finding the resultant of several stresses acting on a body, are the starting points for all structure design.

MECHANICS

The subject of mechanics is broadly divided into two parts: (1) bodies at rest, dealing with structure and supports, such as used in electric distribution construction; and (2) bodies in motion, such as machinery, gears, and wheels, involving time and space change.

There are four fundamental quantities in mechanics:

Space in one direction is length and is commonly measured in terms of feet. In two directions, it is area and is measured in terms of square feet, etc. In three dimensions, it is volume and is measured in terms of cubic feet, etc.

Force always causes some change in the dimensions of a body. A force always tends to produce some change in motion of the body upon which it acts.

Mass is the amount of material in a body. The common unit for measuring mass is the weight in pounds.

Time.—The standard of time is a day, set by the earth's rotation around the sun. Any part of the day is commonly measured in hours and minutes.

Laws of Equilibrium.—There are two principles that are at the foundation of all calculations for bodies or structures that are at rest.

1. The sum or total of all forces acting on a body is equal to zero. The sum of forces in any direction equals the sum of those in the opposite direction.

This is readily apparent when we keep in mind that if it were not true, the body would not be at rest, but would be moving in the direction of the excess force.

2. The sum of moments clockwise around a point is equal to the sum of moments counterclockwise around the same point.

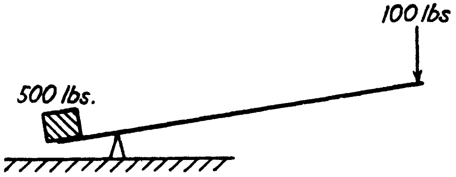


FIG. 144.—A mechanical advantage of 5 to 1.

This is illustrated in the common balance, or in a teeter-totter; the weight on one end, times its distance from the point of support, is equal to the weight on the other end, times its distance to the support. It is apparent that, if this were not true, the arm or member would rotate.

Mechanical advantage is obtained by applying this latter principle usually to bodies at rest which we wish to put in motion.

For example, when we use a bar to lift a heavy weight by placing a support called the "fulcrum" nearer the end that is placed against the heavy weight and then pull on the long end of the bar, we are able with a few pounds pull to move a much heavier weight. If we are able to move a 500-lb. weight by exerting a 100-lb. force, in the lever arrangement of Fig. 144, we have obtained a mechanical advantage ratio of 5 to 1.

We are also applying this principle when we use a rope and pulley arrangement. The mechanical advantage is equal to the number of ropes supporting the load. If we have four ropes, for example, as shown in Fig. 145, we can lift a weight four times as heavy as the effort or pull we place on the free end of the rope.

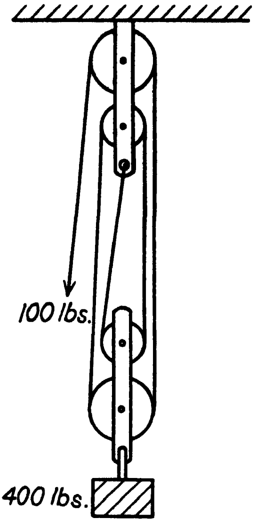


Fig. 145.—A mechanical advantage of 4 to 1.

STRENGTH OF MATERIALS

Whenever any body is acted on by external forces, there is a resulting tendency to disrupt the body. An internal force in the body of material resists this tendency, and this force is called *stress*. There are five kinds of stress—tension, compression, shear, bending, and twist. These forces cause a *strain* in the body of material, and different materials and shapes have different resistances to them.

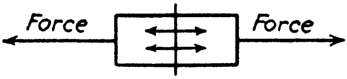


Fig. 146.—Tension.

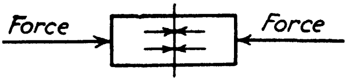


Fig. 147.—Compression.

Tension.—A body is said to be in tension when it is subjected to two forces acting in opposite directions, *away* from the body and *along the same straight line*, as shown in Fig. 146. Conductors of the line, guy wires, and ropes are the most common examples of distribution materials in tension.

Compression is the opposite of tension—the forces act *toward* the body, as shown in Fig. 147. Concrete foundations are the most common of bodies subjected to simple compression.

Shear is the result of forces *not* in the *same straight line.* There is a tendency to cut the material in two, as we would with a large pair of shears (Fig. 148). Bolts, screws, and rivets are in shear.

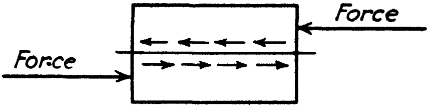


FIG. 148.—Shear.

Bending is caused by *three or more forces* acting along a body, as in the balance or push bar (Fig. 149). A pole supporting a corner in the line, and not guyed, is subject to this stress.

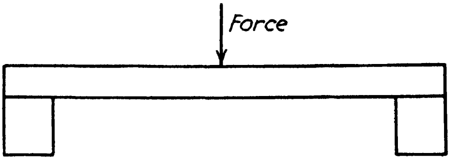


FIG. 149.—Bending.

Twist is more common in moving bodies, as in drive shafts (Fig. 150). One example in distribution structures is the twist caused by line tensions that are not equal, on the two sides of a pole or tower. A severe twisting force may result when a wire breaks between supports.

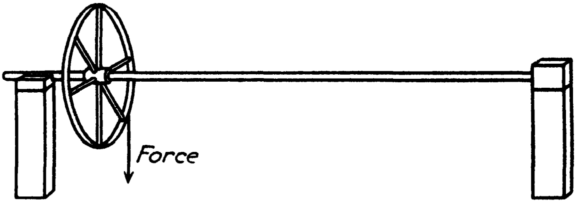


FIG. 150.—Twist.

Elasticity is the property of a material that enables it to recover its original shape and size after being stressed. Every material has a limit, and stress beyond that point will cause a certain amount of permanent deformation or set. The load that causes this permanent change is called the *elastic limit* of the material.

Ultimate Strength.—Beyond this elastic limit point, the material still resists the stress but has lost certain of its original characteristics. A further increase in load or force causes breakdown, yield, or rupture. This point is the ultimate strength, or breaking strength. For some materials, as glass, the elastic limit and the ultimate strength are very nearly the same. Most materials, however, show the deformation or yield point of elastic limit at a lower value than the breaking or ultimate strength.

Ultimate strength values for common structural and building materials are given in reference handbooks in pounds per square inch or cross section of material. For steel supports, special formulas are necessary to interpret the strength to actual values for the particular cross section and shape—angles, channels, I-beams, etc. For common distribution construction materials, these values are given for actual stranding and material treatment conditions.

TABLE VI.—STRENGTH OF GALVANIZED STEEL STRAND (GUY WIRE) IN POUNDS

Size, in.	Common	High strength	Extra high strength	Weight, lb. per 1,000 ft.
¼	1,900	4,750	6,650	121
5/16	3,200	8,000	11,200	205
⅜	4,250	10,800	15,400	296
½	7,400	18,800	26,900	517
⅝	11,600	29,600	42,400	813

From N.E.L.A. Overhead Systems Reference Book.

TABLE VII.—STRENGTH OF COPPERWELD GUY STRAND IN POUNDS

Size, in.	No. and size of strand	High strength	Extra high strength	Weight, lb. per 1,000 ft.
	3 No. 10	3,140	3,722	87.1
	3 No. 8	4,629	5,621	138.5
5/16	7 No. 10	7,758	9,196	203.7
⅜	7 No. 8	11,440	13,890	323.9
½	7 No. 6	16,890	20,460	515.0

From Copperweld Steel Co. E.D. 1686.

Standard steel used for guys has an elastic limit of 24,000 lb. per square inch and an ultimate strength of 47,000 lb. per square inch. A ¼-in. diameter guy has elastic limit of 1,000 lb. and ultimate strength of 1,900 lb. High-strength steel used for guys has elastic limit of 69,000 lb. and ultimate strength of

125,000 lb. per square inch. A ¼-in. guy of this material, for example, has elastic limit of 2,800 lb. and ultimate strength of 4,750 lb. Values for some common sizes of guy wires are given in Table VI. In Table VII are shown strengths of some sizes of Copperweld guy strand.

Copper Wire Strength.—Copper wire is made in three standard grades of hardness and strength, depending on the drawing and annealing processes used. Hard-drawn wire is stiffer and harder to handle but has high strength. Medium-hard-drawn wire is between hard and soft-drawn, and soft-drawn is very flexible and easily handled, but of relatively low strength.. Conductors for inside wiring are usually soft-drawn, for primary lines medium-hard is most common, and for long span lines hard-drawn wire is used. Strengths of several sizes of copper wire, of hard- and soft-drawn grades, are shown in Table VIII.

An important method of increasing strengths, particularly with the smaller conductors, is to use one strand of steel with several strands of copper or aluminum. Steel strands, for strength, are also used with strands of aluminum wire, to build up high-strength conductors. Aluminum wire by itself has very low tensile strength.

TABLE VIII.—COPPER WIRE

Size of wire, solid	8	6	4	2	0	00	000	0000
Ultimate strength:								
Hard drawn	830	1,280	1,970	3,000	4,520	5,520	6,720	8,140
Soft drawn		760	1,210	1,930	2,980	3,720	4,740	5,980
Bare wire:								
Weight per foot	0 050	0 079	0 126	0 201	0 319	0.403	0 508	0.641
Resultant loading*	0 873	0 917	0 981	1 07	1 21	1.31	1 43	1 57
Triple braid:								
Weight per foot	0 075	0.112	0.164	0.260	0.407	0.502	0 629	0 767
Resultant loading*	1 00	1 08	1 14	1 28	1 43	1 52	1.69	1. 84

* Resultant loading per foot at 0 degrees Fahrenheit with ½-in. ice and wind pressure 8 lb. per square foot. From N.E.L.A. Overhead Systems Reference Book.

Factor of Safety.—In all designs of mechanical structures, there are a number of variables and possibilities, which make the exact determination of stresses and strengths difficult. It is usual practice to design for the assumed loading conditions and to use a safety factor or multiplier, to be on the safe side. These factors, usually of the order 1.5, 2, etc., make allowance for the difference between elastic limit and ultimate strength, to avoid permanent deformation, and also make allowance for variations from average quality.

Safety Standard.—The National Electrical Safety Code is our nearest approach to a national standard and reference for construction practices. It lists requirements such as strength, clearances, and loading bases, together with guiding principles for electrical lines crossing other lines, roads, etc

MECHANICAL DESIGN

The principal problems in line design start with the tensions of the conductors and their resulting loads on the supporting poles or towers. Tensions of the conductors depend on the weight of the material and the tightness to which we pull them It is apparent that the tighter we pull the conductor, that is, the greater the tension, the less will be the amount of sag. Weight per foot, distance between supports, or span lengths, sag in the span, and tension are, therefore, our ruling factors in line design.

Temperature changes cause a further change in the sag and tension after installation. The total length of the wire, and, therefore, the sag, increases and decreases with increasing and decreasing temperature. Stated more simply, the wire is drawn tighter in cold weather, and the sag increases in warm weather.

Ice and sleet on the wires add to the dead weight of the wires. For purposes of design, it is assumed that the ice forms in a uniform coating around the wire. A ½ in. radial thickness of ice is assumed in northern areas, and ¼ in. in central areas This is an important addition to load. For example, on No. 0 wire, ½ in. of ice adds ½ lb. per foot, which is more than the weight of the wire.

Wind pressure is another loading, which adds at right angles to the weight of the wire and ice loading. The wire and ice load is vertical, or downward, and the wind pressure is horizontal, or across the line. The resultant causes a greatly increased tension in the conductor, when compared with that caused by the weight of wire alone. For a 60 mile per hour wind, the pressure is 8 lb. per square foot of projected surface of wire and ice coating.

Sag and tension relations are among the most important of design features. It is desirable to keep sag to a minimum to prevent the wires swinging together, yet a large sag is desirable to minimize the stress in the wires and the supports. The answer must, therefore, be a compromise.

Sag and tension tables may be based on some ruling, or average, span. Sags and tensions are then calculated for each size of wire used and at several temperatures, as 30, 60, and 90 degrees Fahrenheit. An example is shown in Table IX.

TABLE IX.—EXAMPLE OF SAG AND TENSION TABLE

For triple braid, copper wire, with span average 130 ft.

Sag in inches. Tension in pounds.

Temperature and loading	6		2		0		00		0000	
	Sag	Tens	Sag	Tens.	Sag	Tens.	Sag	Tens.	Sag	Tens.
30°F.	16	180	15.5	425	14.5	707	14	887	14	1,370
60°F.	20	143	20	332	19.5	531	19.5	660	19	1,032
90°F.	24.5	116	24.5	271	23.5	439	23.5	545	23.5	828
Heavy loading	38	720	28	1,160	23.5	1,560	21	1,810	18.5	2,520

Another example, for one size of wire, is shown in Table X. Here the sags are shown for several span lengths, which may be necessary for rural lines, etc. Longer spans than the 300 ft. shown are in common use in many localities.

In these tables, the resultant loading of ice, wind, and low temperature is shown as the maximum condition for the design. These values of tension are used in guying calculations, and the sag and tension figures at the nearest temperature are used at the time of installation.

TABLE X.—NO. 4 HARD DRAWN BARE SOLID COPPER WIRE

Temperature and loading	Tension, pounds	150	200	240	275	300
		Sag, inches—Span, feet				
30°F.	462	9	15	24	31	37
60°F.	377	11	20	29	38	45
90°F.	312	14	24	35	46	55
Heavy loading	1180	22	39	56	73	87

Physical conditions of a line include these factors of wire and ice weight and their resultant, with wind pressure, together with span lengths and angles in the line. These data are the statement of loading on the supports, and from it we determine strength and material requirements.

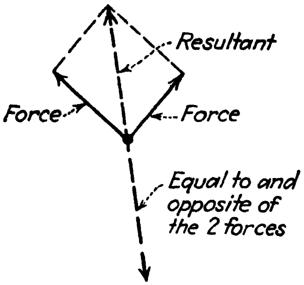


FIG. 151.—Resultant and equilibrant of two forces.

Solution of Design Problems.—The first step in any design is, as we have noted in discussion of transformer connections,

Draw a diagram

On this mechanical diagram, represent each of the forces by an arrow indicating its direction. Free the diagram of all non-essentials, and simplify it by letting one line represent all forces that can be combined, as several wires in one direction.

For the more complicated structures, special formulas may be necessary, although the graphical methods may also be used for many steps in the solution.

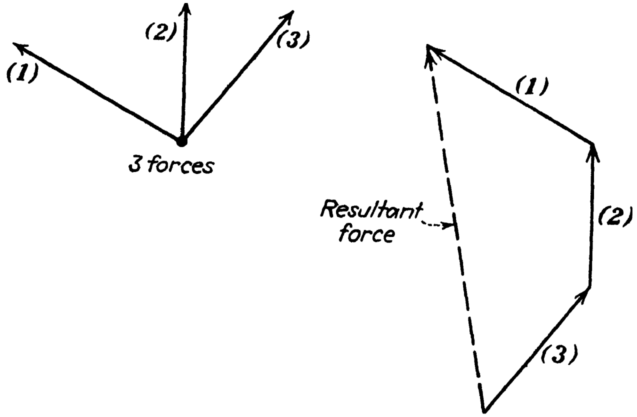


FIG. 152.—Addition of several forces to give their resultant.

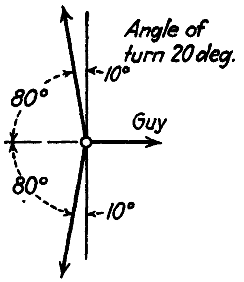
Graphical Solutions.—Magnitude of a force is shown by the length of a line, and the direction in which it is acting is shown by its position and an arrow. Two principles are used to simplify the solution from this point:

1. Two forces can be resolved into one by the "parallelogram of forces." The resultant is the diagonal of a parallelogram

constructed on the arrows. The equilibrant is equal and opposite to their resultant (Fig. 151).

2. One force may be resolved into two forces acting in given directions by constructing a parallelogram of which the diagonal represents the given force, and the sides of which have the given directions.

Several forces acting on one point, as several services from a pole, are added together in a similar manner, as indicated in Fig. 152. When mechanical problems involve forces that can be resolved to right-angle components, the coordinate chart, that we have used for electrical problems, can be used to advantage. This is the case with guying problems, which are the most common field calculations required. A number of charts and curve methods have also been developed for quick reference solution of these problems.



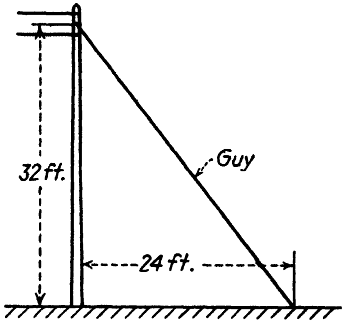


Fig. 153.— Example for calculation of guy tension.

Example: Find the tension in the guy under conditions shown in Fig. 153, with pole supporting 4 No. 00 primary wires, 3 No. 2 secondary wires, and 2 No. 6 street light wires, all triple braid covered. The guy is attached 32 ft. up on the pole, and the anchor is 24 ft. from the butt of the pole. The angle turn of the line is 20 degrees.

For the heavy loading condition of Table IX, the tension in each wire is: 720 lb. No. 6; 1,160 lb. No. 2; and 1,810 lb. No. 00. The total tension in each direction is then

4 No. 00	4 × 1,810 =	7,240 lb.
3 No. 2	3 × 1,160 =	3,480 lb.
2 No. 6	2 × 720 =	1,440 lb.
Total	=	12,160 lb.

The guy is to be located in a direction opposite to the resultant of the two forces Each force is 12,160 lb , and it acts at an angle of 80 degrees from the resultant The component on the resultant is, from the chart, 2,150 lb The resultant of the two forces is

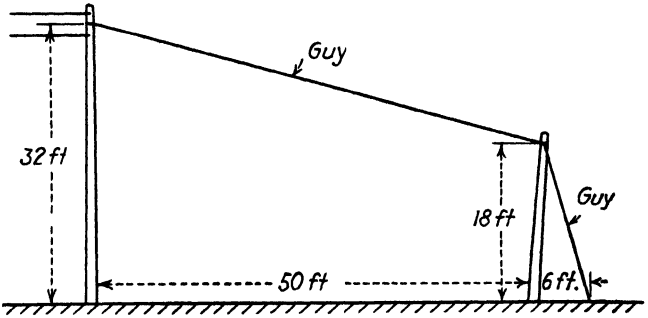


Fig 154 Problem Guy tensions

$$2 \times 2{,}150 \text{ lb} = 4{,}300 \text{ lb}$$

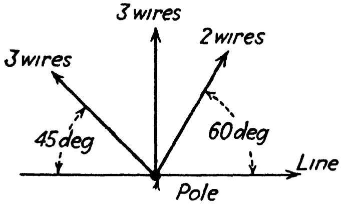


Fig 155 Problem Find resultant force

This resultant is in the plane of the wires We must now find the increased tension required when the resultant is replaced by a force acting away from the horizontal plane

The angle between the guy and the horizontal is found on the chart. horizontal scale, 24, and vertical scale, 32, angle 53 degrees

Now, the horizontal component of 4,300 lb gives, at 53 degrees, a force of 7,150 lb , which is the tension in the guy

Problems·

1. What is the tension in the guy for the line of example (4 No 00, 3 No 2, 2 No 6), at a 40-degree corner, if the anchor is 40 ft from the butt of the pole?

2 If the guy of the example, 20-degree turn, is to a stub 50 ft from the pole, is shown in Fig 154, (*a*) what is the guy tension and (*b*) what is the tension in the stub guy?

3. With a factor of safety of 1 25 what size of Copperweld guy wire would you use for each of the preceding guys?

4. What is the resultant pull on the pole, with 3 services as shown in Fig 155, if the maximum loading condition gives 500 lb tension in each wire?

CHAPTER XV

ECONOMIC PRINCIPLES IN DISTRIBUTION

In the opening chapter, Perspective of the Electric System, it was pointed out that the final test for every addition and development must be: "What has this to do with delivering a continuous, steady, economical supply of electrical energy to the point of consumption?" This question is of fundamental importance in the distribution division of any system. Growth of load, expansion of service areas, and increasing dependence on electric service necessitate constant application of planning and engineering for expansion, enlargement, and improvement of the distribution system.

In this chapter are reviewed some of the economic factors that influence decisions on standards, methods, and materials. The question of cost and economics has been mentioned in every one of the previous chapters. In the following chapter, the other two factors of our question will be reviewed, also from the standpoint of delivery to the consumer.

COMPANY FINANCE

It is not within the scope of our electric distribution study to consider the many and intricate problems of finance, accounting, economics, rate schedules, and cost studies involved in the operation of an electric system. It is essential, however, that those engaged in, and responsible for, construction and operation of a distribution system understand, and often apply, many of the economic fundamentals involved.

Because most of us do not see the bills that come in every day, we may not have given thought to the fact that a company, even as an individual, must keep its expenses within its income—must have money on hand or in the bank to pay the bills. When we buy a pair of shoes, an automobile, or a house, or pay the grocery bill, we go through the same general motions that our company does when it buys a load of poles, a bank of transformers, or a new generator, or pays its coal bill.

All our expenses can be classified under three headings—investment, operation, and maintenance.

Investment or capital items are those we continue to use over a considerable period of time—our home, automobile, and some of our clothes. Our company has power plant equipment, substations, pole lines, and many other items in this class. They represent capital invested in the business. The capital investment required in the electric utility business is the highest, when compared with annual revenue, of any business. The investment is four to five times the annual revenue, compared with the typical industrial enterprise that has investment less than the annual revenue.

Operation items are those that are consumed soon after we purchase them—food, gasoline, coal. Broadly, electric operation means the labor, material, supplies and expenses to produce, transmit, and distribute electrical energy.

Maintenance is the upkeep of our property, painting, reshingling the roof, etc. In the electric distribution system, it covers repairs, renewals of minor items, and replacements due to storms, etc., to keep the plant up to its original or equivalent state of usefulness.

Investment Costs.—When we buy a home or an automobile, we either borrow money on which we must pay interest or use money that we could otherwise invest to draw interest. We must, over a period of time, repay the borrowed money. The individuals who organize a utility corporation must have or must borrow funds with which to build the electric plant. As further expansion to serve customers is made, additional funds must be invested by those who have money available and on which they expect to earn interest. For a growing business, this investment and financing side necessitates constant attention to keep money available to pay for the new equipment.

When the investment is made for the new plant, whether it be a generator, or a new transmission line, or only the service line to a house, the investment costs start. Interest, repayment, and taxes must be paid whether there is a full load of current, or very little, flowing through this item of the plant. It must be maintained as long as it is in use, and these costs depend on what is installed rather than what load is carried. Similarly, these costs are on our automobile, whether we drive once a week or a great amount.

Operation and maintenance costs, on the other hand, are made up of a number of items that vary with the load, others that vary with physical and surrounding conditions, and others that are independent of load. Coal costs and some other operating costs depend directly on the load, but meter reading, accounting, record expense, and other items do not. Painting, repairs after storms, replacement of equipment that fails, and similar items depend more on surrounding conditions than directly on load.

Money available to meet these costs, to pay employees, coal bills, taxes, interest, and to buy materials and equipment can come from only two sources.

1. *Invested or borrowed funds*—bonds, which are mortgages on the property; stock investment in the business; loans to meet expenses.

2. *Revenue or income from sale of energy,* based on the rates and amount of sale of electrical energy. Rates are broadly in two parts: (*a*) demand or service charges, to meet investment and flexible costs; and (*b*) energy charges, to meet operating costs.

Money paid out is (1) to meet pay roll for wages and salaries; (2) to pay taxes; (3) to pay bills for supplies, coal, new materials and equipment; and (4) to pay interest and dividends on borrowed and invested funds.

Reserves set up from income are equivalent to our personal savings to meet expected extra expenses—Christmas, vacation, doctor bills. They are essential in business to meet the annual payments of interest, repayments, retirement of bonds, etc., and for emergencies and unforeseen construction.

Regulation.—Because electric utilities have certain grants of rights to use the public streets, because the competition between electric service companies in one area is restricted, and because of the vital interest of the public in electric service, the utility business and rates are subject to much closer government regulation than are other manufacturing and retailing businesses. Rates are subject to close scrutiny, and the history has been one of constantly decreasing income for each kilowatt-hour sold, necessitating constant increase in the total kilowatt-hours to maintain stable financial conditions.

ECONOMIC COMPARISONS

For the distribution economic comparisons, it is not ordinarily necessary to have exact data on rates, financing, and costs, since there are many variables in these studies that cannot be determined to extreme exactness. This is particularly true because load conditions, demand, energy used, density of customers, and rate of growth affect the distribution requirements so directly.

About one-half of the investment in an electric system is in the transmission and distribution division. The cost of kilowatt-hours at the generator bus is only a fraction of the final cost at a residential customer's meter. In Chap. I, a comparison of an electric system was made with the usual manufacturing and retail system. This comparison extends to costs also. The retail cost of a suit of clothes, for example, must include not only the cost of cloth and work on the suit, but also the other costs of operating a factory—building expenses, taxes, etc. It must include shipping and possibly warehouse expense and, in the store, the expense of selling and advertising and of operating the store. Having the suits available also means an investment charge in the suits, and in the many others from which we can make our selection.

This latter item is parallel to a very important similar cost in electric operation—the readiness to serve or availability of energy. And, in the case of electricity, this availability means as much as wanted, when wanted—and with no previous notice. The lines, transformers, substations, and the generators and boilers must be ready to furnish the desired amount of electrical energy exactly when it is wanted. This condition ordinarily means that transformer and service equipment costs are determined by the maximum demand on the service, or on the feeder, to meet conditions that may occur only occasionally. A striking example is the capacity requirement of many loads that are used at their maximum for only a few evenings previous to the Christmas season.

Investment Comparisons.—Initial, or first, costs can be compared directly, and this is the usual first step. Based on estimates for alternate plans, they are most important in determining the general layout, location of substations, and voltage to use for new lines. They are also used to compare radial and network systems, series and multiple street lighting plans, long span and short span line construction, etc.

Beyond these direct estimates are the less easily determined estimates of growth of load, density of customers, and depreciation of equipment. Whether or not the additional refinement of annual cost comparisons are made, the estimates of first cost are necessary.

Annual Costs.—Comparisons, to determine the lowest annual cost, are the most important application of economic principles in distribution design and layout. Several important examples have been discussed in previous chapters: line costs, page 41; wire size determination, page 62; power factor improvement, page 92; transformer comparison, page 119.

Annual costs on investment are conveniently summarized as a percentage rate, which is applied to the costs of purchase and construction. These investment costs, also called fixed charges, are added to the cost of losses for different designs, in comparisons to determine the most economical transformer purchases, most economical wire size, and other similar problems.

This type of comparison is applicable wherever an increase in efficiency, or decrease in losses, is obtainable with an increase in investment. We can aim too high in reduction of losses, by using larger wire or by raising equipment efficiency, and have the savings more than canceled by the increases in investment cost.

An interest rate of 6 to 7 per cent is commonly used to cover interest on the money and the cost of financing, or raising the money.

Property taxes vary, 2 or 3 per cent being average.

Depreciation varies according to the physical and surrounding conditions and also because of functional or obsolescence conditions. This subject is considered in some detail in later paragraphs. A rate of 3 to 6 per cent is commonly used.

Maintenance also is a factor of annual costs based on investment, but since it will ordinarily not vary much with changes in efficiency, or losses, within the limits of usual comparison, it may be omitted.

These rates total a minimum of 11 per cent and a maximum of 16 per cent. Most commonly used rates are between 12 and 14 per cent.

Cost of losses may be considered as the increment cost of energy lost only or as the total cost of energy including investment charges up to the point for which comparison is made, depending on the conditions. When metered energy is being lost, as with customers' wiring, the energy rate should be the minimum or bottom block or step, as changing losses will not affect the demand or first-use blocks. In our transformer comparison example (page 120), we used ½ cent per kilowatt-hour, and in the wire size determination example, we used 3 cents per kilowatt-hour. That losses on the electric system represent a very real cost of operation may be understood from the fact that they average 10 to 20 per cent of the total energy generated.

Formulas and rules, similar to those used in electrical and mechanical calculations, cannot ordinarily be used for economic studies. Ohm's law for finding current is based on terms of fixed and definitely measurable quantities. Cost studies, in contrast, are based on quantities that vary with many other conditions. For a given set of conditions, certain conclusions regarding other variables may be stated, but when they are applied to different conditions, they may be entirely misleading.

Such conclusions may, however, be of considerable value. An example is as follows: For a given type of construction and within reasonable limits, the cost of distribution per customer varies inversely with customer density. Other similar conclusions have helped in distribution load studies and system plans, but attempts to assign definite dollar values in formulas to determine cost per customer, or per unit of energy sold, etc., can be more confusing than useful.

Kelvin's law is a statement of economic comparison that is useful—if properly applied. It expresses the annual cost comparison for conductors: The most economical size of conductor is that for which the annual charge on the investment is equal to the annual cost of energy loss. This is derived from the fundamental idea of seeking the minimum annual cost and remembering that *both* investment costs and loss costs are factors in the total.

DEPRECIATION AND OBSOLESCENCE

Depreciation is the change in usefulness of plant, lines, and equipment that leads to replacement. It is of fundamental importance in the economics of electric systems, as well as all business facilities and investment. Depreciation of plant may be considered in three parts:

1. Physical depreciation due to deterioration and wearing out of the parts in service, as represented by poles rotting, hardware rusting, etc.

2. Obsolescence due to inadequacy, which accompanies load growth beyond that provided for in the original construction. This has been the largest factor in distribution replacements. Lines constructed even ten years ago may now be carrying twice the load then expected.

3. Obsolescence due to new developments and improvements. Perhaps the most notable example in the electric system is in the power plant design where turbines replaced reciprocating-type engines and higher pressures and temperatures successively increased possible efficiencies.

Obsolescence due to inadequacy and to new developments, (2) and (3), have ordinarily been considered together, but it is well to distinguish the separate parts. In distribution, obsolescence has, in general, accounted for much more replacement than has physical depreciation. Few important parts of substations and lines are removed because they can no longer perform as they were expected to when they were installed. In many cases, they are salvaged and used at other locations, but their original installed cost, or the investment required to put them in service, must be replaced.

Even knowing that load increases may make lines we install today inadequate in a few years, we are not necessarily justified in changing this factor of inadequacy. A cost comparison between No. 6 wire that will carry the load now and No. 2 wire that will be needed a few years hence will include the rate of growth or years before the change is necessary and the cost to change. This form of comparison was mentioned in the discussion of loading of distribution transformers and is applicable in secondary arrangements and primary feeders as well.

Transformers, which represent large unit investment and are relatively easier to change than wire, can be economically changed much more often than can secondary or primary lines. For example, it is good practice to install No. 2 wire for secondary, supplying six spans in each direction from a 5-kva. transformer, even though No. 6 wire would carry this load satisfactorily. As the load increases, the transformer can be changed and two transformers installed to cut down the secondary distance, meanwhile leaving the No. 2 wire in service.

Salvage of materials has been an important part of distribution operations, since so much hardware, poles, wires, and equipment have had to be removed as larger lines were required. Transformers are, of course, easily moved from one location to another. Hardware can be regalvanized, poles can be cut to shorter lengths to remove rotted sections, wire can be used again—but it must be remembered that they have depreciated as far as their original installed value is concerned.

ESTIMATES—WORK ORDERS—ACCOUNTS

In the preceding paragraphs, we have considered some of the economic factors that govern the selection of methods, materials, and equipment for use on the distribution system. The principles in comparisons of this kind are naturally based on the broad framework of financing the business, although the degree of exactness possible in other factors does not warrant exact detail in determining the costs.

There is another part, however, to our interest in these economic questions, and it is of necessity quite detailed. To those charged with providing service to our customers, the first requirement is to build the line and to install the transformers and then to keep the service available. That is right, but it does not mean that we can drop our interest in that particular service as soon as it is cut in or restored. It is essential that our work be recorded, the costs placed on the company's books, and the money we have spent set into the proper accounts.

Most manufacturing and retail business investment is in a limited area, in one or several buildings, or yards. It is possible, and common practice, to have a periodic inventory or check of the equipment, stock, and goods on hand. In the case of an electric distribution system, the investment is scattered, perhaps over thousands of square miles. It is along the streets, roads, and private rights of way, overhead and underground, on customers' premises, and in their buildings. The system is constantly being changed, as wire, equipment, poles, and service installations are replaced, moved, and added to meet changing customer load requirements.

Good management as well as public regulation requires that these changes in property and investment be placed on the records. Charges must be so reported that investment, depreciation or retirement reserve, or maintenance accounts will reflect the changes in physical layout that we have made. When an entirely new line is built or an old one removed, this is fairly simple, but when we extend a line and replace some wire and hardware in the present line, we must have a clear picture of the accounts involved.

To facilitate this procedure, account numbers are assigned to all the principal types of installations and to the corresponding operation and maintenance items. For example, in one system,

Account 354 applies to poles and fixtures
Account 355 applies to overhead conductors
Account 356 is for underground conduit
Account 360 is for meters
Operation account:
  3412 Operation for poles and fixtures
  3458 Maintenance for poles and fixtures
  3416 Operation for transformers
  3466 Maintenance for transformers

These series of numbers are extended to all the principal parts of the system, to readily identify the pay roll, material, and expense charges when they are sent to the accounting group for recording, and they assist us in classifying our charges.

Estimates are made after an inspection of the drawings and conditions in the field, to determine the necessary additions for a new or enlarged service or extension. The estimated costs are based on unit costs for similar previous jobs. When approved, they become *work orders* or job orders, which are authorities to proceed with the construction. *Retirement* estimates similarly show the value of property that is expected to be removed.

Charges are made to these work orders as the work is carried on. When completed, the order is returned to the accounting office, and all the charges are shown on one or more sheets which are placed in the books.

In addition, maps, drawings, lists of material, and work order numbers used must be placed in operating office files to show the physical changes made, and to tie in with the dollar changes recorded in the account books.

Budgets are preliminary estimates to show expected requirements several months or a year in advance. They provide an opportunity for discussion of proposed major expansion and growth, such as new substations, feeders, and lines. Their primary purpose is to provide management with a basis for planning necessary financing, so that the money will be ready when the bills come in.

SUMMARY

Economic comparisons are somewhat more definite application of the same sort of reasoning that we all use in our personal affairs (Table XI). Some of us buy as inexpensive suits as we can, and others of us pay more on the basis of getting longer use—we use the expression, "It's cheaper in the long run." Some of us

TABLE XI.—ECONOMIC OUTLINE—COMPARISON OF COMPANY AND PERSONAL ACCOUNTS

	Personal	Company
Capital investment	Build a house Labor, material Architect, supervision	Power plant, stations, lines Labor, material, equipment Engineering, supervision
Annual investment costs	Interest Insurance Taxes	Interest and dividends on bonds and stocks Taxes
Reserves	To pay off debt To buy new furnace	To pay off the debt or to provide for depreciation
Maintenance	Repair plumbing, furnace Paint house. To maintain value	Replace insulators, poles, etc. To keep property and investment in its original state of usefulness
Operation	Coal to heat house Water, electric supplies	Coal, operating costs. Materials, supplies consumed

use low-cost gasoline in our automobiles, and others pay 2 or 3 cents more per gallon because we expect to have lower cost per mile.

Added complications in distribution expenditures include the factors of load growth and longer periods of time. The more flexible and variable the factors that control cost, the more experience and judgment are required in applying economic controls. Cheap materials or small lines are usually not good economy, but it does not follow that increasing the capacity or the efficiency or quality beyond a certain point is economical either.

For our daily work, in applying construction standards to definite situations, we must keep in mind that it is not sufficient to build the line or restore service, even though that is of primary importance. We must also report what we did and what it cost, so that the charges can be properly accounted. Rates, income, regulation, company policy, financial stability, although perhaps remote in our operating problems, are none the less of fundamental importance to continued rendering of a reliable and steady electric service.

CHAPTER XVI

MEASURES OF SERVICE

Electric service is, as we have noted in a previous chapter, much broader than making available a supply of electricity. It includes our efforts and service and constant adjustments and rearrangements to keep not only the supply available, but also the service satisfactory. From the standpoint of equipment operation, we check our annual summaries of line outages, transformer failures, voltage and load surveys, etc. From the standpoint of service, our customers sum this all up in a feeling of good will, or otherwise.

Electric distribution is the division of the electric supply system that carries energy to the customer's wiring. To the customer whose lights go dim or off, it matters little whether the cause is in front of his own house, in the substation, or the result of a major system disturbance. The result to him is annoyance and inconvenience. It is more serious to have several thousand customers affected by a major trouble than it is to have one, or fifty, or one hundred affected by a blown primary fuse. But when viewed at the end of a year, the total number of customers inconvenienced and the total loss of good will may be much greater from the many individual troubles than from the one or two major troubles.

In the early days of electric service, a several hour outage might go unnoticed, if it did not occur during the evening when lights were wanted. Use of appliances gradually changed this expectancy. Electric refrigerators and then electric clocks and radio receivers have changed it entirely. The increasing attention given to lighting as well as the interest in radio has made the customers more conscious of voltage conditions as well.

Acceptance of electric supply for driving machinery and for other uses in factories has from the beginning made a constant supply imperative to operation. In commercial service, continuity of supply is of vital interest also, since elevators, as well as lighting, are essential to activity in stores and offices. The fact of general acceptance and reliance indicates that electric service has measured up to these requirements.

In general merchandising distribution, three measures are most important—supply, quality, and cost. Similarly, three measures are applicable to electric service—availability, character of voltage, and cost. The keynote of all the preceding chapters has led up to these measures: from the standpoint of the customer and the load, to make electric service available, to furnish satisfactory voltage, with the greatest economy possible for the conditions.

AVAILABILITY—CONTINUITY OF SERVICE

Availability is naturally of first importance. After the service facilities are constructed and installed, availability means continuity, or the absence of interruptions. Outages, equipment failures, and other troubles are usually summarized annually on the basis of number per 100 miles of line, or per 100 units of equipment, per year. A summary of feeder outages is shown in Table XII. Other examples were shown in the section on transformer operation. These summaries assist in outlining maintenance and construction policies and are as important in supervising operation as the annual accounting report is in supervising business policies.

TABLE XII.—FEEDER OUTAGES—URBAN AND SUBURBAN

Feeder relayed out during storm	9	
Wire burned down by lightning	5	
Failure of lightning arrester	3	
Lineman caused short circuit	1	
Wires down by causes beyond control	8	
Failure of pothead	1	
Failure of station equipment	9	
Outage of transmission circuit supply	34	
Total feeder outages	70	
Outage due to distribution line trouble	27	
Per 100 miles		4.7
Fuses blown on overhead branch lines	56	
Per cent (598 locations—971 total fuses)		5.8
Total overhead troubles per 100 miles of line		14.8

To obtain these records, it is, of course, necessary to inspect and check each case of trouble. The inspection must include all conditions of the installation or construction that might in any way contribute to the trouble or that might contribute to remedies and corrective measures. Many examples of this form of advancement could be given, but one or two will suffice to illustrate the point.

It was noted in the annual review of feeder outages that a large number were caused by trouble beyond fused points. Trouble at a large transformer, instead of causing the primary fuse to blow, might cause the whole feeder to be relayed open. Wires down or crossed, on a fused tap from the main line, might cause an outage on the feeder instead of on the branch only. Preliminary consideration indicated that relaying open of the feeder switch was due to (1) too close adjustment of relays, (2) too slow blowing of the fuse at some values of short circuit current, or (3) shattering of the fuse box and failure to clear.

Tests of fuses, studies of short circuit currents, and plotting of time-current curves for both the relay settings and the fuse characteristics, as shown in Chap. XI, indicated the sources of trouble. This led to development of new types of fuse links, more careful application of fuses, and to closer checking of time of fuse blowing, as shown in the curves for coordination of protection. As these improvements were made, outages were reduced on 140 feeders: 24 feeder outages from this cause in 1930, 16 in 1931, 8 in 1932, none in 1933, and one or none each year since.

A similar series of tests and investigations, with both distribution operators and protective equipment manufacturers participating, led to the general improvement of grounding for lightning protection. Investigations on the lines showed that troubles occurred most frequently where grounding resistance was high and less frequently where the grounding conditions were better. This conclusion checked with theoretical and test considerations and led to interconnection of grounding at transformer installations and installation of "counterpoise" grounding and lower tower grounding on transmission lines.

Summary figures of availability, although not used directly in determining what changes in maintenance and operating policies should be made, can serve the same purpose as many of the percentage and ratio figures set up by accountants to summarize all the detail data. A formula that gives a very good measure of service is the percentage of connected capacity to serve that is available to the customer. Expressed in another way, it is the capacity hours total of outages compared with capacity hours available if no outages had occurred.

Thus, a 10-kva. transformer that failed and required 1 hr. for replacement results in 10 kva.-hr. outage. A 1,500-kva. feeder out of service for two minutes adds 50 kva.-hr. to the total. For an urban system, this ratio of outage may be 2 or 3 kva.-hr. outage per 100,000 kva.-hr. operation. On suburban lines, this ratio may go to two or three times this value, and on rural lines it will probably be several times the suburban value. Table XIII shows such a summary.

TABLE XIII.—KILOVOLT-AMPERE-HOUR OUTAGES IN PARTS OF 100,000 KVA-HR. IN OPERATION

Central division	Distribution trouble				Transmission or substation trouble	Total
	Feeder outage	Branch line fuse	Transformer fuse or failure	Total		
32 urban feeders	0.71	0.80	0.62	2.13	0	2.13
32 suburban feeders	0.68	1.14	1.39	3.21	1.46	4.67
14 rural feeders	2.80	2.40	0.74	5.94	14.70	20.64

Trouble Calls.—Perhaps one of the best indications of the dependence that the public has come to have on electric service is the promptness with which outages and troubles are reported. Replacement of customers' fuses is commonly a part of electric service, and this policy is of value in quick restoration of service following interruption caused by the distribution equipment. When customers are in the habit of immediately calling when the lights or appliances are out, local outages of distribution lines and equipment can be promptly handled.

It is usually possible to know within a few minutes, from the locations of trouble calls, whether to dispatch a man to a transformer for one group or to a section of line that is affecting a large area. Another important advantage of handling all outage calls is that proper size fuses will be installed. Thus, many cases of strapped fuses, oversize fuses, and pennies behind blown fuses are avoided. And, the very tangible value of customer good will possible with these services is of importance.

Several comparative analyses of outage records show that electric service companies should not overlook the conditions of inside wiring, in studies to improve service continuity. Interruptions caused by troubles in the customers' wiring may, in many cases, equal or exceed those caused by troubles in the primary supply.

VOLTAGE CONDITIONS

In considering system layout, line design, and equipment application, we have noted the fundamental importance of voltage control. Design for nearly all primary supply circuits is based on voltage drop limitations, and special equipment is provided to compensate for drop. Changes in load conditions, however, necessitate constant attention to the adjustments, installations, and equipment sizes.

Inside wiring, beyond the utility meter, often complicates efforts to maintain proper voltage. Operation of lamps and appliances is naturally affected by the drop in this part of the complete system, as much as it is by the circuit ahead of the meter. In residential, and to perhaps a less extent in commercial, wiring installations, these wiring facilities have lagged far behind the load increases. Wiring originally used for lighting load has, largely within the past ten or fifteen years, been called upon to carry appliance load also. This has doubled the average energy consumption and greatly expanded the voltage control problems. This has been discussed in a preceding section, but is mentioned again here because it has an important bearing on measures of service at the customers' equipment.

There are three methods of maintaining voltage control, which also give a measure of its effectiveness:

1. *Periodic tests* at selected points on each feeder, with chart voltmeters to give a 24-hr. or longer record, are the principal basis for the feeder regulator control. These tests are essential in the operation and adjustment of the regulators, to compensate for load increases, shifts in the load center, and to find possible troubles in the control adjustments.

These checks may also be supplemented with voltage readings taken at transformer secondaries and also at secondary ends, by the transformer load-reading inspectors (page 112).

2. *Service entrance* readings of voltage, by the troublemen who answer customers' trouble calls, also give a detailed check of voltage conditions, supplementing the periodic tests made on the main circuits outside. After replacing a blown fuse, these tests of voltage can be made very quickly. High and low readings are checked by voltage inspectors and often lead to correction of poor conditions that might otherwise be overlooked.

A curve of 25,565 readings, for one year, is shown in Fig. 156. The average of these readings was 120.2 volts, with 27 per cent at 120 volts, 18 per cent 121 volts, etc. Of the total readings, 70 per cent were between 118 and 122 volts. These data, with 2,623 transformer secondary readings, averaging 121.1 volts, and 3,169 secondary end readings, averaging 119.5 volts, gave a very broad picture of voltage conditions.

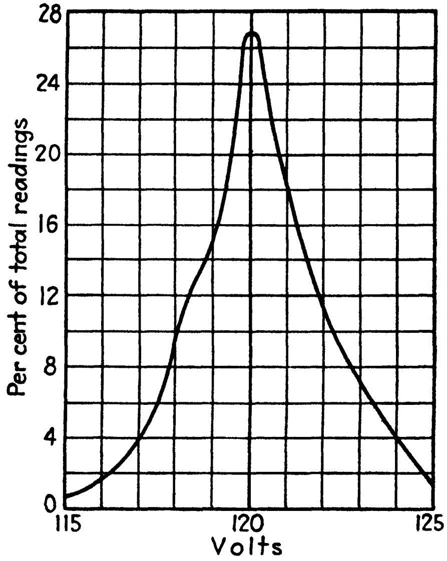


Fig. 156.—Service entrance voltage readings.

3. *Complaints* received from customers are both a means of maintenance and a measure of effectiveness of voltage control. Naturally many complaints are not justified, but many of them are, and none should be considered as "kicks." In Table XIV is shown a tabulation of complaints for one year. Of the total received, one-half were found to be justified. For the division covered by this tabulation, 2.3 complaints were received per 1,000 residential and commercial customers.

In this summary, voltage fluctuations due to refrigerator load on secondaries are classified as due to "overloaded secondary lines," and the loose connection causes include service entrance switch connections. It is interesting to note that about twice as many high-voltage complaints were received as low voltage, but the justified complaints were equal, high and low. Often, a complaint is the first notice received by the company of additions to the customer's load, since most appliances can be installed without necessity for notice or application.

TABLE XIV.—VOLTAGE COMPLAINTS

	Number	Per cent
Voltage complaints checked	353	
Found justified	172	49
Found voltage normal	181	51
Reported high	157	45
Found high	44	25
Reported low	72	20
Found low	43	25
Reported fluctuating	124	35
Found fluctuating	85	50

Summary of causes of justified complaints:

Overloaded primary	9
Overloaded transformer	7
Overloaded secondary	56
Overloaded service	12
Loose connections	27
Load unbalanced	5
Wiring or appliances	9
Regulator adjustment	21
Transformer trouble	2
Wrong primary phase	10
Miscellaneous	14
Total	172

Radio interference is a special form of voltage condition. Radio receivers are very sensitive to certain conditions that would not affect lamps or other appliances. Originally, electric distribution equipment was one of the principal causes of radio interference. Loose connections at cutouts, taps, and terminals and arcing at insulators and to ground were the principal causes encountered. Tests, inspection, design changes, and maintenance have, in general, removed this source as a widespread cause, but cases of loose and corroded connections and faulty equipment still occur often enough to require investigation of the complaint. Table XV shows a summary for one year, with the 21 per cent that were traced to electric supply line causes listed in detail.

TABLE XV.—RADIO INTERFERENCE COMPLAINTS

	Number	Per cent
Radio complaints received	309	
Electric service caused	64	21
Customers' appliances	45	15
Radio set trouble	71	23
Other utilities caused	15	5
Unfounded or disappeared	114	36

Causes of electric service interference:

Primary plug-type fuses	8
Primary wood box fuses	2
Primary porcelain box fuses	5
Lightning arresters	4
Secondary trouble	6
Arc lamp or circuit	7
Tree grounds	15
High-voltage line discharge	9
Voltage fluctuation	4
Other causes	4
Total	64

A rather liberal policy has been followed by the utilities of the United States in investigation of radio interference complaints. The utility cannot say that its equipment is not causing trouble without an investigation, because such cases still occur. The inspector can usually trace down the real cause at a moderate additional cost and not only promote good will, but thus also check conclusively that the distribution lines are not at fault. Radio receivers are one of the best consumers of kilowatt-hours, among domestic appliances. In general, the cost of a liberal policy of complaint investigation will approximate only about 1 or 2 per cent of the revenue derived from radio as a load.

Radio interference causes are of two classes. The most common are those associated with load current passing through loose connections in circuits or equipment and those generating radio frequency energy. Somewhat less common are the cases of static discharges to ground from electrical conductors or charged bodies, but not associated directly with load current. Loose ground connections are the most common causes of static discharge interference. Loose connections at transformer installations were formerly the most common cause of load current interference. Loose connections at appliances, in the house wiring, and the frequent breaking of current in thermostatically controlled appliances, and in electric signs, medical treatment and similar devices are now more frequently the cause of this type of interference.

Among the technical developments in radio reception have been the elimination of the necessity for a long outside antenna. This has, however, to some extent increased the radio interference problem, because the connection to the electric outlet and the electric wiring adjacent to the radio receiver serve in the reception of radio frequency waves. At the same time, this wiring may reradiate interference frequency from other appliances or loose connections in the wiring. Along with the growth in receiver use, there has been a growth of appliance use. Many of these appliances may act as miniature broadcast stations sending out, either directly or over the electric wiring, impulses that interfere with the frequency of the broadcast and may be picked up by the sensitive radio receiver.

SUMMARY

Electric service has become essential to public convenience, and in many cases interruptions are actually hazardous. Expenditures to further increase reliability of electric supply should take cognizance of all the factors of use and dependence. Thus, network systems are justified for supply to central business areas in large cities, with supply from more than one source, but they are not justified in suburban residential areas. Two sources, automatic switching, duplicate transformer installations, and other similar facilities, are considered in terms of the justified extra expenditure to ensure improvement of continuity.

Importance of uninterrupted service to residential customers' wiring has increased as the use of electric refrigerators, for example, has increased. Other appliances and uses of electricity have each added to this importance, and even short outages are noticed. This condition has grown rapidly in the past few years, and improvements have in general kept service in pace with the requirements.

We can summarize operations by the number of units that fail, and this is the basis for close study, but we should also measure the records in terms of customer service outage. A blown primary fuse or a transformer failure in service means a certain cost for repairs or replacement, but that measure is of secondary importance compared with the value of continuity.

This measure must be considered in conjunction with that of cost. The question in many cases may be, "Is a large increase in investment justified to prevent a few minutes per year outage?" A close study of present operations is warranted for possible improvement of continuity, along with the costs for such improvement.

Satisfactory service, steady voltage, absence of fluctuation, and reliability have become parts of electric supply that are taken for granted. Attention to these measures and a close balance with cost have brought the steady and rapid acceptance of our product for use in residential, commercial, and industrial operations

We can perhaps close with the thought expressed in an opening paragraph. The function of electric distribution is to deliver to those who can use electric current and who need it to operate lights, motors, and appliances the energy that can be most efficiently generated in a central station. Perspective of the system and of developments, understanding of the uses of electricity, and appreciation of the factors of service beyond delivery –these fundamentals are important to us, along with technical knowledge of equipment, calculations, and measurements.

APPENDIX

MATHEMATICAL REVIEW

It is essential, in any approach to a study of electrical principles, that we have clearly in mind certain mathematical principles. Electric distribution, perhaps more than any other application of engineering, involves the solution of numerical problems in everyday activities. Arithmetic and other branches of mathematics are shorthand methods of expressing and clarifying statements.

We all use the fundamental principles of mathematics in our personal affairs—most often, perhaps, with dollar signs involved. In studying electric distribution, we must use some other terms, volts, kilowatts, etc., but handling the figures is the same. Determination of wire size and voltage regulation involves familiar arithmetic steps but requires some practice to keep the terms in their proper relationship.

Multiplication.—An $\times$ between two numbers indicates multiplication: 4×2 is read "4 times 2," or "4 multiplied by 2."

Equation.—The sign $=$ means equals or indicates an equation between the quantities before and after it Thus;

$4 \times 2 = 8$, means that
4×2 is equivalent to 8

Division is indicated by the sign $\div$ or it may be shown by one number over another with a — between

$4 \div 2$ is also written $\frac{4}{2}$
and means, "4 divided by 2"

Fractions and **ratio** are based on division. Both express one quantity divided by another: $\frac{4}{2}, \frac{1}{2}$. Both terms of a fraction or a ratio may be multiplied or divided by the same number, with no change of value. Thus;

$$\frac{4}{2} = 2$$

and

$$\frac{4 \times 2}{2 \times 2} = \frac{8}{4} = 2$$

and

$$\frac{4 \div 2}{2 \div 2} = \frac{2}{1} = 2$$

Transposition of figures from one side of an equation to the other follows from the above. In

$$2 \times 6 = 3 \times 4$$

we can divide both sides by 2

$$\frac{2 \times 6}{2} = \frac{3 \times 4}{2} \qquad \text{or,} \qquad 6 = \frac{3 \times 4}{2}$$

which is

$$6 = \frac{12}{2}$$

Similarly,

$$2 \times 6 = 3 \times 4$$

is the same as

$$\frac{2 \times 6}{3} = 4$$

Also we can add or subtract the same number from both sides of an equation

$$\begin{aligned} 2 + 2 &= 4 \\ 2 &= 4 - 2 \end{aligned}$$

and

$$0 = 4 - 2 - 2$$

Squares.—The sign ^{2} after and a little above a number indicates the square of that number. Thus, 3^2 means 3×3, the number multiplied by itself.

Square root, indicated by $\sqrt{}$ is the reverse

$$3 \times 3 = 9 \qquad \text{and} \qquad \sqrt{9} = 3$$

Similarly, 3^3 means $3 \times 3 \times 3$, which equals 27,

and

$$\sqrt[3]{27} = 3$$

Percentage.—There are several ways of expressing the ratio of the part to the whole. One-quarter of a dollar is ¼ of $1. It is also 0.25 of $1, or 25 per cent of $1. When we express it as 0.25, it is the decimal value, and 25 per cent or 25% is the percentage.

It is convenient to use percentage, as in speaking of interest we say 6 per cent. When using this rate in a multiplication, we change it to a decimal. Thus;

6 per cent on a loan of $20
0.06 × $20 = $1.20

This is the same sort of problem as voltage regulation. Thus;

3 per cent of 120 volts
0.03 × 120 = 3.6 volts

Decimal points offer one of the most common sources of error of any of the common mathematical steps. An answer of 155 amperes when we should get 15.5 amperes is of the same nature as deciding we owe $155 when it really is $15.50. The steps are shown in these examples:

(1) $\frac{300}{15} = 20$

$$\begin{array}{r} 20. \\ 15/\overline{300} \\ \underline{30} \\ 0 \end{array}$$

(2) $\frac{300}{1.5} = 200$

$$\begin{array}{r} 20\ 0. \\ 1.5/\overline{300.0} \\ \underline{30} \\ 0\ 0 \end{array}$$

(3) $\frac{300}{.15} = 2{,}000$

$$\begin{array}{r} 20\ 00. \\ .15/\overline{300.00} \\ \underline{30} \\ 0\ 00 \end{array}$$

(4) No. 2 wire has a resistance of 0.161 ohm per 1,000 ft.

(*a*) What is the resistance of 8,000 ft.?

$$\begin{array}{r} .161 \\ \underline{8.000} \\ 1.288\ 000 \end{array} \text{ or } 1.288 \text{ ohms}$$

(*b*) What is the resistance of 450 ft?

$$\frac{450}{1{,}000} = .45 \qquad \begin{array}{r} .161 \\ .45 \\ \hline 805 \\ 644 \\ \hline .07245 \end{array} \text{ ohm}$$

Is the Answer Reasonable?—Care will keep the decimal points straight, but a good check rule is to approximate the answer. In (*a*) above, 8,000 is nearly 10 times as much as 1,000 ft. and 10 × 0.161 = 1.61, so an answer of 1.28 is reasonable. In (*b*), 450 ft. is about one-half 1,000 ft., and one-half of 0.161 is about 0.08, therefore 0.07 is reasonable.

Problems to be solved as a check of these points:

1. Divide $25 equally among 4 men. What is each share?
2. Divide one of these shares among 10 boys. What is each?
3. Divide $25 between 2 men so that one gets 1.5 times as much as the other.
4. The resistance of No. 2 wire is 0.161 ohm per 1,000 ft. What is the resistance of 500 ft.? of 750 ft.? of 1,400 ft.? of 1,800 ft.?
5. What is the I^2R loss ($I \times I \times R$) in a wire carrying 24 amperes (I) and having a total resistance (R) of 4.07 ohms?

Significant Figures.—In practical problems, we can save time and energy if we remember that we are dealing with the result of measurements. A voltmeter with a scale to read 120 volts cannot show 121.365, and a distance of 365.1 ft. is as practical as an answer of 365.083 ft.

Solution of Problems.—Experience shows that most of us are prone to pass over mathematics when we are reading a text. Often, there is more to be gained by working through a few lines of figures than there is in reading several pages and skipping over the figures.

Of equal importance to the actual solution of problems is *seeing* what they apply to. Because volts and amperes are not visible, this may seem difficult, but a few sketches, even roughly drawn, are an aid. A diagram of connections, a few vectors or forces shown by arrows, and a triangle as shown for the graphical solution of line problems are all helps in keeping the steps clear. And, this is just as true in the most exact trigonometric calculation as it is in the quick field check of a problem.

Step by Step Method.—Draw a diagram or sketch. Write down the known factors, as load, volts, etc. Find the current.

Use the graphical method of solution, or sketch the values on such a diagram, solving by mathematics. Check the answer by approximation—is it reasonable?

FORMULAS

There are three fundamental terms in electrical circuit problems. They are expressed in *Ohm's law:*

An ampere is the current produced by a force of one volt in a circuit having a resistance of one ohm.

$$\text{Current in amperes} = \frac{\text{Force (voltage)}}{\text{Resistance in ohms}}$$

$$I = \frac{E}{R} \quad \text{and} \quad E = I \times R$$

The unit of power is the watt.

The unit of work is the watt-hour.

$$\text{Current in 1-phase circuit} = \frac{\text{Watts}}{\text{Volts} \times \text{P.F.}}$$

$$\begin{array}{c}\text{Current in 3-phase circuit} \\ \text{(current in each wire)}\end{array} = \frac{\text{Watts}}{\sqrt{3} \times \text{Volts} \times \text{P.F.}}$$

(NOTE: $\sqrt{3} = 1.73$ is important in all three-phase calculations.)

ABBREVIATIONS AND SYMBOLS

a.c.	alternating current	kw.	kilowatt
d.c.	direct current	kw.-hr.	kilowatt-hours
E or V	voltage, volts	kva.	kilovolt-amperes
I or A	current, amperes	rkva.	reactive-kilovolt-amperes
R	resistance, ohms	hp.	horsepower
W	energy, watts	c.m.	circular mils (wire size)
P.F.	power factor		
K	one thousand		

APPROXIMATIONS

It is often helpful to remember a few values for quick use to reduce the amount of calculation necessary for frequently met problems. With these, and similar values, we can make a simple multiplication of kilovolt-amperes times amperes, instead of the division otherwise necessary. For example:

1 kva. 1-phase at 2,400 volts: Current = 0.42 ampere
1 kva. 1-phase at 240 volts: Current = 4.2 amperes
1 kva. 3-phase at 4,150 volts: Current = 0.14 ampere
1 kva. 3-phase at 240 volts: Current = 2.4 amperes

Resistance Value.—It may be useful at some time when a table is not at hand, to be able to approximate resistance and circular mil sizes of copper wire. We remember the following:

No. 10 wire is 10,000 c.m. and has a resistance of 1 ohm per 1,000 ft. The circular mil size *doubles* and the resistance *halves* for each increase in wire size of *three* numbers.

No.	Double c.m.	Fill in	Halve ohms	Fill in
10	10,000		1.	
9		13,000		.82
8		16,000		.66
7	20,000		.5	
6		26,000		.41
5				.33
4	40,000		.25	
		etc. to 0000		

Current carrying capacity is not directly proportional to circular mil size. For rough approximations, however, the following will help:

Wire in the open, with weatherproof or other insulations, will carry one-quarter to one-half *more* current than rubber insulated wire. *For weatherproof wire:*

a. Small sizes (10, 8, 6) carry about 3 amperes per 1,000 c.m.
b. Medium sizes (4, 2, 0) carry about 2 amperes per 1,000 c.m.
c. Large sizes (2/0, 4/0) carry about 1½ amperes per 1,000 c.m.
d. Very large wires carry about 1 ampere per 1,000 c.m.

Hp. to Kva.—For approximation: 1 hp equals 1 kva., for induction-type motors. This rough value accounts for the usual values of efficiency and power factor and the ratio of 746 watts per horsepower.

TABLE FOR COPPER WIRE

Size A.W.G. solid*		14	12	10	8	6	4	2	0	00	000	0000	←Stranded——→					
Circular mils		4107	6530	10,380	16,510	26,250	41,740	66,370	105,500	133,100	168,000	211,600	250M	300M	400M	500M	750M	1000M
Safe carrying capacity, amperes — Rubber ins.		15	20	25	35	50	70	90	125	150	175	225	250	275	325	400	525	650
Safe carrying capacity, amperes — Other ins.		20	30	35	50	70	90	125	200	225	275	325	350	400	500	600	800	1000
Resistance, ohms per 1,000 ft.		2.52	1.59	.9989	.649	.407	.257	.161	.1010	.0805	.0638	.0505	.0437	.0364	.0273	.0219	.0146	.0109
	½	.0687	.0634	.0581	.0528	.0475	.0422	.0369										
	1	.0846	.0793	.0740	.0687	.0634	.0581	.0528	.0475	.0450	.0424	.0397	.0365	.0344	.0311	.0286	.0250	
	2	.1004	.0952	.0900	.0846	.0793	.0740	.0686	.0634	.0609	.0583	.0556	.0524	.0503	.0470	.0445	.0419	.0377
	6	.1256	.1203	.1150	.1097	.1044	.0991	.0938	.0885	.0860	.0834	.0807	.0775	.0754	.0721	.0696	.0663	.0628
	8	1322	.1269	.1216	.1163	.1110	.1057	.1004	.0952	.0926	.0900	.0873	.0841	.0820	.0787	.0762	.0727	.0693
	10	.1373	.1321	.1267	.1215	.1163	.1109	.1055	.1003	.0979	.0953	.0926	.0894	.0873	.0840	.0815	.0781	.0746
	12	.1415	.1362	.1309	.1256	.1203	.1150	.1097	.1044	.1019	.0993	.0966	.0934	.0913	.0880	.0855	.0823	.0787
	15	.1466	.1413	.1360	.1308	.1255	.1202	.1148	.1095	.1070	.1044	.1017	.0985	.0964	.0931	.0906	.0874	.0839
	18	.1508	.1455	.1402	.1349	.1296	.1243	.1190	.1136	.1102	.1086	.1059	.1027	.1006	.0973	.0948	.0915	.0881
	21	.1544	.1491	.1437	.1385	.1332	.1278	.1225	.1170	.1145	.1119	.1092	.1060	.1039	.1006	.0981	.0949	.0915
	24	.1574	.1521	.1468	.1415	.1362	.1309	.1256	.1203	.1178	.1152	.1125	.1093	.1072	.1039	.1014	.0982	.0947
Distance, inches between centers of conductors	30				.1466	.1413	.1360	.1307	.1255	.1229	.1203	.1176	.1144	.1123	.1090	.1065	.1025	.1000
	36				.1508	.1455	.1402	.1348	.1296	.1271	.1245	.1218	.1186	.1165	.1132	.1107	.1073	.1042
	42				.1544	.1491	.1437	.1384	.1332	.1307	.1281	.1254	.1222	.1201	.1168	.1143	.1109	.1078
Inductive reactance, ohms per 1,000 ft for 60 cycles	48				.1574	.1521	.1468	.1414	.1362	.1337	.1311	.1284	.1252	.1231	.1198	.1173	.1140	.1108
	60				.1625	.1572	.1519	.1466	.1413	.1389	.1363	.1336	.1304	.1283	.1250	.1225	.1192	.1158
	72				.1667	.1614	.1561	.1508	.1455	.1431	.1405	.1378	.1346	.1325	.1292	.1267	.1233	.1202

* Inductance of stranded conductors is .0013 ohm less than for solid of same size.
Values for No. 8 and larger, from N.E.L.A. Overhead Systems Reference Book.
Safe carrying capacity values are from National Electrical Code.

ANSWERS TO PROBLEMS

Chapter II

1. 72% **2.** 78 kw., 97½ kva. **3.** 428 kva, use 450 kva. bank **4.** Demand factor 50% Load factor 33%

Chapter V

1. (*a*) 208 amperes No. 0000 wire (*b*) 3.1 amperes No 14 (*c*) 50 amperes No. 6
2. 22.2 volts **3.** 755 watts, 95% **4.** No. 2 wire **5.** No. 4 wire
6. No. 0000 wire, 8.4 volts drop, 1,750 watts loss, 500,000 c.m.
7. Not enough saving to pay for the larger wire

Chapter VI

1. No. 2 wire, $R = 0.161$ ohm, $X = 0.105$ ohm **2.** (*a*) No 0000 (*b*) 300,000 c.m. (*c*) 400,000 c.m. (*d*) 750,000 c.m.
For (*a*) $R = 0.0404$, X at 2 = 0.0445, X at 10 = 0.0741
3. 78% **4.** 382 amperes before, 287 amperes after **5.** (*a*) $R = 0.814$, $X = 0.291$ (*b*) $R = 1.288$, $X = 1.005$ (*c*) $R = 3.40$, $X = 5.52$
6. All correct

Chapter VII

1. (*a*) $Z = 0.865$ ohm (*b*) $Z = 1.63$ ohms (*c*) $Z = 6.50$ ohms
2. (*a*) 416 amperes (*b*) 240 amperes (*c*) 555 amperes (*d*) 320 amperes
3. 11.5 volts **4.** 4,840 volts, 16.6% regulation
5. 382 rkva., 75% P.F. **6.** 537 rkva., 81% P.F.

Chapter VIII

1. 98.3% at full, 98.5% at ½ **2.** 75 kva. at 100%, 50 kva. at 150%
3. Purchase Bank *A*

Chapter IX

1.

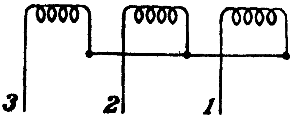


FIG. 157.

2. Will not parallel as shown. Reverse leads to 1 and 3 on either bank
3. No **4.** Does not cause reversal

Chapter X

1. 4.5% **2.** 2.4% **3.** No. 14 wire 0.126 + j 0.0067 No. 2 wire 0.097 + j0.060 **4.** (*a*) 3.4% end of secondary and 4.5% at main switch. (*b*) 5.0% and 6.1% (*c*) 3.2% and 4.3%
5. Drop 2.25% O.K. without starter **6.** 9.4%

Chapter XI

1. 10 cycles **2.** No, could not be coordinated. Fuse would blow in 15 cycles **3.** 1,300 amperes **4.** 2,700 amperes

Chapter XIV

1. 11,000 lb. **2.** (*a*) 4,700 lb (*b*) 14,000 lb. **4.** 3,475 lb.

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